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Landfill Gas Production from Large Landfill Simulators

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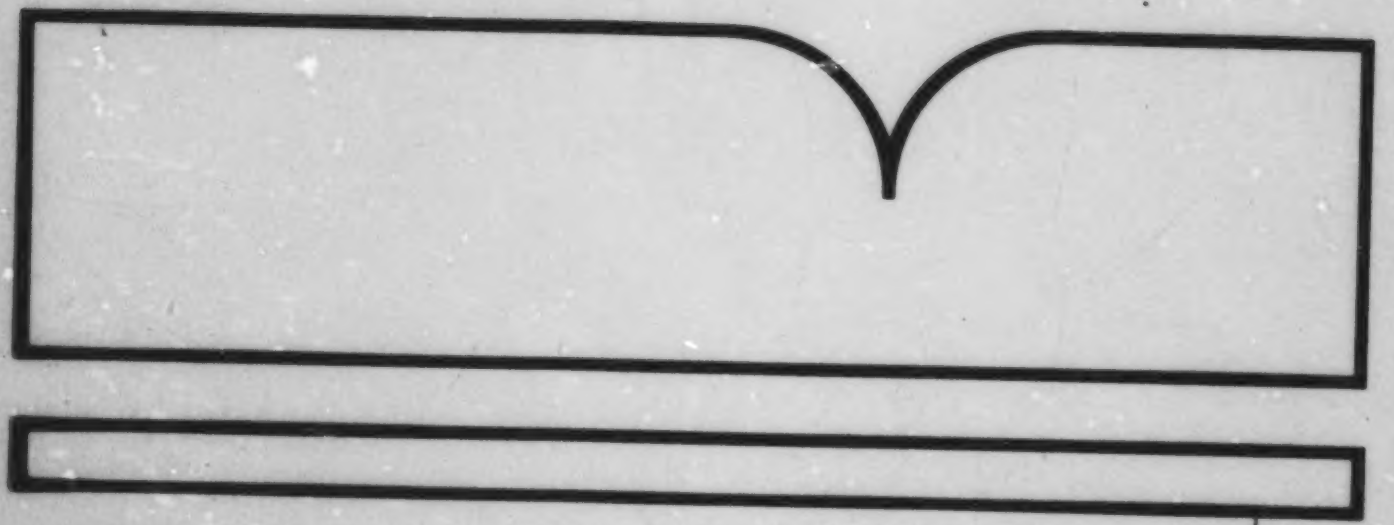

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LANDFILL GAS PRODUCTION FROM LARGE LANDFILL SIMULATORS

by

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USAE Waterways Experiment Station
Vicksburg, MS 39180

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16. ABSTRACT

Two sizes of landfill simulators or test cells; one set containing approximately 320 kg wet weight of municipal solid wastes (MSW) and the other set containing 2555 kg wet weight of MSW were used to measure the amount and composition of gases produced from MSW under typical landfill conditions. The relative amounts and gas compositions follow those reported by other investigators.

The two sizes of simulators produced very similar volumes of gas when the gas production is considered on a unit weight of MSW basis. The small simulators produced 17.75 ml of gas per kg dry MSW per day; the large simulators produced 20.1 ml of gas per kg dry MSW per day. However, methane production was generally nigher for the small simulators than for the large simulators.

This study demonstrates that the conditions present in the average MSW landfill are not ideal for maximum production of methane; but large quantities of methane can, nevertheless, be produced over the active decomposition period of landfilled MSW. Further studies on the effects of environmental and microbial nutritional factors on methane production in landfilled MSW are recommended.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is a necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This study examines the problem of gas production from landfilled municipal wastes. Studies such as this advance our understanding of techniques

developed for managing (i.e. landfilling) solid waste with minimum impact on human health and the environment, and with an eye to harvesting an energy return from this proper management.

Francis T. Mayo, Director

Municipal Environmental Research

Laboratory

ABSTRACT

Two sizes of landfill simulators or test cells; one set containing approximately 320 kg wet weight of municipal solid wastes (MSW) and the other set containing 2555 kg wet weight of MSW were used to measure the amounts and composition of gases produced from MSW under typical landfill conditions. The relative amounts and gas compositions follow those reported by other investigators. An aerobic phase typified by decreasing oxygen levels and increasing carbon dioxide concentrations appeared first. This phase was followed by a non-methanogenic, anaerobic phase typified by production of carbon dioxide, nitrogen and hydrogen. The third phase, the unstable methanogenic phase, was typified by the sporatic appearance of methane in the outflowing gas. The fourth phase, the stable methanogenic phase with methane and carbon dioxide as major gases, was just being reached when the experiment was terminated.

The two sizes of simulators produced very similar volumes of gas when the gas production is considered on a unit weight of MSW basis. The small simulators produced 17.75 ml of gas per kg dry MSW per day; the large simulators produced 20.1 ml of gas per kg dry MSW per day. However, methane production was generally higher for the small simulators than for the large simulators. Total methane production for 630 days of decomposition was 0.096 ml per kg dry MSW for the small lysimeters compared to 0.038 ml/kg dry

MSW for the large cells. The smaller cells consistently produced much less hydrogen (0.025 ml/kg dry MSW) than the larger cells (0.158 ml/kg dry wt MSW) over the first 630 days of decomposition.

An automated gas measuring system developed for this study functioned satisfactorily in monitoring the four landfill simulation test cells. The gas chromatograph-based gas-analysis, system functioned satisfactorily. Gas samples were collected in an all-metal collection system; plastic and glass gas sampling vessel proved unsatisfactory.

This study demonstrates that the conditions present in the average MSW landfill are not ideal for maximum production of methane; but large quantities of methane can, nevertheless, be produced over the active decomposition period of landfilled MSW. Further studies on the effects of environmental and microbial nutritional factors on methane production in landfilled MSW are recommended.

CONTENTS

Foreword iii

Abstract v

Figures ix

Tables xi

Acknowledgment xiii

1. Introduction 1

2. Conclusions and Recommendations 4

3. Methods and Materials 9

Test Cell Construction 9

Gas Flow Measuring and Sampling systems 15

Data Reduction and Presentation 23

4. Results 25

Leachate Production Rates and MSW Moisture Retention 25

Leachate Characteristics 29

Overall Gas Production Rates 36

Gas Composition 43

5. Discussion 73

Scaling Effects of Test Cell Size 73

Development of Gas Production 76

Factors Affecting Gas and Methane Production 79

References 82

FIGURES

Number		Page
1	Schematic diagram of the municipal solid waste test cells . . .	10
2	Detail showing method of sealing the tops of the test cells . .	10
3	Facility for housing landfill simulator project	16
4	Schematic diagram of gas flow measurement and sampling system	16
5	Position of gas collection probes in the large test cells . . .	17
6	Detail of construction of gas collection probes	17
7	Temperature, barometric pressure, and gas flow for day 18, test cell #15	37
8	Temperature, barometric pressure, and gas flow for day 80, test cell #15	38

Number Page

9 Total gas produced by large test cells summed over 14 day periods 41

10 Total gas produced by small test cells summed over 14 day periods 42

11 Percent of carbon dioxide in gas from test cells over time of experiment 53

12 Total volume of hydrogen from large test cells summed over 14 day periods 57

13 Percent of methane in gases from test cells over entire experiment 63

14 Percent of methane in gases from test cells over duration of the experiment 67

TABLES

Number		Page
1	Test Cell Sizes and Loading	12
2	Percent Composition of MSW Used in This and Other Studies	13
3	Comparison of Average Water Balance Values for Small and Large Test Cells	26
4	Leachate Volumes Produced and Retained	27
5	pH-Values for Leachates	30
6	Conductivity Values for Leachates	32
7	Total Mass of Parameters Leached per Kg Dry MSW	34
8	Volume of Gas Produced Per Day From Test Cells Over Two Week Periods	40
9	Volume of Gas Produced Per kg Dry MSW Day for Test Cells Over Two Week Periods	44
10	Volume of Oxygen and/or Argon Produced Per Day in Test Cells Over Two Week Periods	46
11	Percent of Oxygen and/or Argon in Gas From Test Cells	47
12	Carbon Dioxide Produced Per Day for Test Cells Over Two Week Periods	50
13	Percent of Carbon Dioxide in Gas from Test Cells	51
14	Volume of Carbon Dioxide Produced per kg Dry MSW Day in Test Cells Over Two Week Periods	54

Number		Page
15	Volume of Hydrogen Produced Per Day in Test Cells Over Two Week Periods	56
16	Percent of Hydrogen in Gas From Test Cells	58
17	Volume of Hydrogen Per kg Dry MSW Day in Test Cells Over Two Week Periods	60
18	Volume of Methane Produced Per Day in Test Cells Over Two Week Periods	61
19	Percent of Methane in Gas from Test Cells	64
20	Percent of Nitrogen in Gas from Test Cells	68
21	Volume of Nitrogen Produced Per Day in Test Cells Over Two Week Periods	71
22	Volume of Nitrogen Produced Per kg Dry MSW Per Day for Test Cells Over Two Week Periods	72
23	Comparison of Gas Produced by the Small and Large Test Cells	75

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CHAPTER 1

INTRODUCTION

Landfilling is the most common method of disposal of municipal solid waste (MSW) and consists of shallow burial of the compacted waste under a thin layer of soil or other cover material. Whenever natural organic matter is buried, it is transformed by the action of microorganisms into a variety of simpler organic materials. The gaseous products of this breakdown of organic material create two major problems as the landfill ages (Fungaroli, 1971). Carbon dioxide produced by the fill goes into solution in the groundwater acidifying it and causing a "hardness halo" and increased corrosion in adjacent aquifers. Methane produced by anaerobic decomposition can migrate off-site and create hazardous conditions in surrounding buildings and construction sites. Many investigators have reported the production of combustible gas from municipal solid wastes when placed in anaerobic environments (Chian, DeWalle and Hammerberg, 1977; Collins and Spillmann, 1982; Colonna, 1976; DeWalle, Chian and Hammerberg, 1978; Eifept and Swartzbaugh, 1977; Engineering-Science, Inc., 1965; Fungaroli, 1971; Ham and Bookter, 1982; Intergovernmental Methane Task Force, 1979; Ramaswamy, 1970; Rovers and Farquhar, 1973; Shafer and others, 1981; Walsh and Kinman, 1979) and increasing emphasis is being placed upon the reclamation of methane from suitable landfills (Carlson, 1976; Intergovernmental Methane Task Force, 1979; James, 1981). Suitable landfills for gas capture generally have great depth of

implaced waste and impervious surrounding materials or liners. Accurate measurement of the composition and amount of gas produced during decomposition of MSW is essential to both understanding the pollution problem and exploiting gas produced a possible fuel source.

Landfills can be considered as uncontrolled, anerobic digestors. Many factors will affect the rate and composition of gas found in the landfill reactor. Among them are the refuse composition, its moisture content, degree of compaction, pH, temperature, and nutrient, metal or toxic material content (Farquhar and Rovers, 1973; McCarthy, 1964; Toerien, 1969). Most of these factors bring about their effects by modifying or controlling the kind and level of microbial activity than occurs in the waste materials. The methanogenic bacteria require complete anaerobicity and are most active under slightly alkaline conditions. Typical decomposition of landfill refuse is brought about by sequential or successive populations of microbes who produce metabolites and environmental conditions conductive to subsequent bacterial populations (Chen and Bowerman, 1974; Farquhar and Rovers, 1973; McCarty, 1964; Walsh and Kinman, 1979).

Several studies have focused upon the production of gaseous products from sealed landfill simulators of various sizes and shapes and under various conditions (Chian, DeWalle and Hammerberg, 1977; Ham and Bookter, 1982; Miller and others, 1976). Of the factors affecting the microbial activity in the landfill test cells, a recent study has indicated that the moisture content and the type of MSW were the major controlling parameters (Chian, DeWalle and

Hammerberg, 1977). The wide variability in the published results from previous experiments indicate the need for a long-term, well-instrumented, landfill simulator study.

The present study was developed to corroborate and add to previous determinations of gas production rates and composition from MSW using improved gas monitoring methodology, and to examine problems related to the size (scaling) of large laboratory simulation tanks. Other investigators have relied upon manometers (Rovers and Farquhar, 1973), wet test meters (Toerien, 1969), and Mariotte flasks (Chian, DeWalle and Hammerberg, 1977). One design proposed incorporated a linear mass flowmeter with automatic flow integration and flow-rate recording (Miller and others, 1976). The gas monitoring project described here parallels the previous work, but with more complete instrumentation. Two sizes of test cells are included in this investigation to allow a broad comparison of the data obtained in this project with that obtained in other experimental systems in the literature. This study uses a completely automated, gas monitoring system on four sanitary landfill simulators (lysimeters or test cells).

CHAPTER 2

CONCLUSIONS AND RECOMMENDATIONS

Two sizes of landfill simulators or test cells were used to measure the amount and composition of gases produced from MSW under typical landfill conditions. The relative amounts and kinds of gases found in this study follow those reported for the theoretical stages of bacterial succession in common anaerobic digestors (Engineering-Science, Inc. 1965; Farquhar and Rovers, 1973; McCarty, 1964). Four sequential phases of microbial activity with typical gas emission characteristics caused by different bacterial populations have been recognized by Farquhar and Rovers (1973) for MSW digestors. They are 1) an aerobic phase, 2) a non-methanogenic, anaerobic phase, 3) an unstable, and 4) a stable, methanogenic phase. Gases produced in the last phase are the most desirable energy source since they usually have a mixture of 45 to 60% methane with the balance, being carbon dioxide (easily removed).

The aerobic or first phase consisted of the rapid uptake of any residual oxygen in the MSW and the concomitant release of nearly equal amounts of carbon dioxide. In this study, this phase apparently took place before the first gas sampling took place. The first sample was taken within 24 to 48 hours after the cells were sealed. Only very low levels of oxygen were found in these samples, possibly due to the high initial temperature of the waste when placed in the cells which would result in high metabolic rates for the

microbiological flora. The second phase, as signaled by large volumes of carbon dioxide production, was also well under way in the first two or three days after cell closure. The total gas output of the cells, which was mainly carbon dioxide and nitrogen, decreased dramatically from these peak values over the next 100 to 150 days as the MSW approached water saturation and leachate production. Hydrogen production was noted in all of the test cells 60 to 90 days before methane was detected in any of them.

Three of the four test cells entered the unstable, methanogenic stage at about the time that leachate began to be produced (between days 250 and 300). Methane evolution was slow and somewhat variable over the remainder of the experiment, attaining 10 to 25% methane only after nearly 4 years of fermentation. The stable methane production stage, with its constant 40 to 60% methane concentrations was never reached in any of the cells over the 1500 days of the study. However, all of the cells were increasing in methane production when the experiment was terminated. Only in one of the small cells did the percentage of methane in the released gas continuously increase, reaching around 26% by the end of the experiment and still increasing.

The lack of the development of stable, methanogenic gas production (phase 4) in the test cells may be caused by less than optimum conditions in the leachates such as low, nitrogen to carbon ratios and low, total volatile acids as substrates for the methanogenic bacteria. Other factors retarding the bacterial flora may have been the lower than optimum temperatures in the uninsulated test cells, high levels of toxic metals or organics, or the acidic pH's of the leachates. It is not uncommon to find stable methane production

in only a few weeks under ideal circumstances (Ramaswamy, 1970), but development times of 100 to 300 days are more common and longer times not unusual (Ham and Bookter, 1982; Intergovernmental Task Force, 1979; McCarty, 1964; Toerien, 1969).

Very little experimental data is available concerning conditions necessary for maximum methane production in materials such as MSW (Farquhar and Rovers, 1973; Ham and Bookter, 1982). Experiments using defined volumes of MSW in test cells such as those used in this work could be used to study management techniques which might be employed to speed the establishment of stable methane production and to maximize the rate of methane production. Simple manipulation of the level of nutrients, minerals and/or the pH of the leachant by addition of amendments to the cover material, or perhaps by recycling amended leachate through the landfill might be useful in maximizing gas production in MSW landfills. This is only possible if ideal conditions are well defined.

Little variation was found in the volume of total gas produced per unit dry MSW for both sizes of test cell (17.75 ml/kg dry MSW per day for the small cells versus 20.1 for the large). Composition of the total gases evolved also were quite consistent for the major gas constituents from all test cells--for the small cells, carbon dioxide was 70.5% and nitrogen 19%; and for the large, 69.6% and 21% respectively of the total gas emitted (all values for the first 630 days of the experiment). The overall amount of fermentative activity in the test cells per unit dry MSW appears to have been quite consistent over this time period. The same consistency is found if the

data for the first 100 days is similarly compared (about 1/2 of the total gas evolved was produced in the first 100 days).

Nitrogen gas was found in relatively high and consistent levels in this study. Although acknowledging that nitrogen gas could be produced by denitrification (Farquhar and Rovers, 1973), most authors assume that nitrogen levels are a measure of the amount of contaminating air drawn into the fill or test cell (Chian, DeWalle and Hammerberg, 1977; Ham and Bookter, 1982; Rovers and Farquhar, 1973). Further study of the source and effects of nutritional and environmental effects on nitrogen production should be made to answer this question. The presence of nitrogen gas at levels typically found in this study could create serious problems for the use of the gas for energy purposes. For instance, levels of 15 to 30% nitrogen in landfill gas would lower its BTU value since nitrogen would then make up from 30 to 60% of the gas volume after the carbon dioxide was removed. Careful monitoring of nitrogen levels is recommended in further studies of methane production.

Considerable variability was found for the amount of flammable gases produced within both sizes of test cells. Hydrogen was the only gas which showed consistent differences in amounts produced between the small and large test cells, and this is possibly accounted for by chance. The smaller cells consistently produced much less hydrogen (0.025 ml/kg dry MSW) than the larger cells (0.158 ml/kg dry MSW) over the first 630 days of the experiment. This could be a consequence of the larger methane production in the smaller

cells (0.096 ml/kg dry MSW as compared to only 0.038 ml/kg dry MSW for the large).

The use of an automated, gas measuring system effectively monitored the volume of gases released from four landfill simulation test cells. Results show that conditions present in the average MSW may not be ideal for maximum methane production but that very appreciable amounts of methane (and carbon dioxide) can be expected from the average landfill over extended periods of time. Further studies of the effects of environmental and nutritional factors on the time of development of stable methanogenic conditions and bacterial populations should allow the conditions in the landfill to be modified to maximize or minimize methane production depending upon the use to be made of the site.

CHAPTER 3

METHODS AND MATERIALS

All gases were collected from four (two each of two sizes) carefully sealed, MSW landfill simulators or test cells. The test cells used were the control cells for a larger study of the effect of the co-disposal of untreated and solidified/stabilized industrial wastes with MSW on leachate quality (Malone and others, 1983). Preliminary results of the overall co-disposal experiment and gas study, test cell design have appeared elsewhere (Myers and others, 1979; Shafer and others, 1981).

TEST CELL CONSTRUCTION

The test cells, or landfill simulators, used in this study were cylindrical, steel (7.25mm rolled plate) tanks. The two smaller test cells (Numbers 10 and 22) were 0.91 m inside diameter and 1.83 m in height; the two larger cells had dimensions of 1.83 m inside diameter and 3.66 m in height. A cross-section of the test cells is shown in Figure 1. All interior surfaces of the test cells were coated with a coal-tar epoxy. The acid- and base-resistant, epoxy layer protected the test cell walls from corrosion and thereby the test cell contents from contamination.

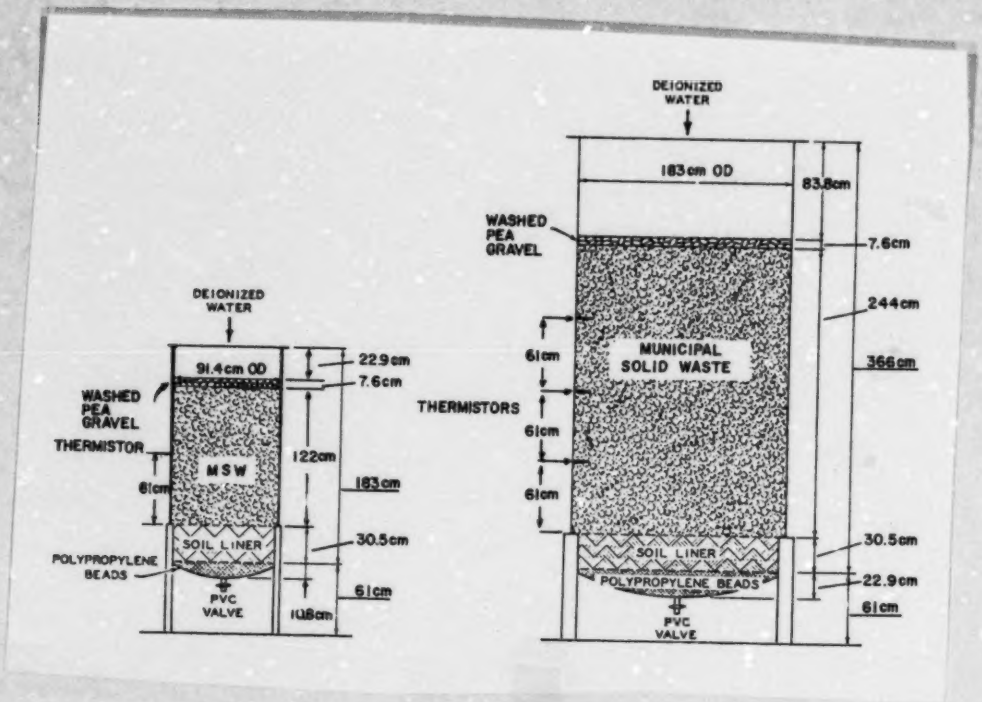

Figure 1. Schematic diagram of the municipal solid waste test cells.

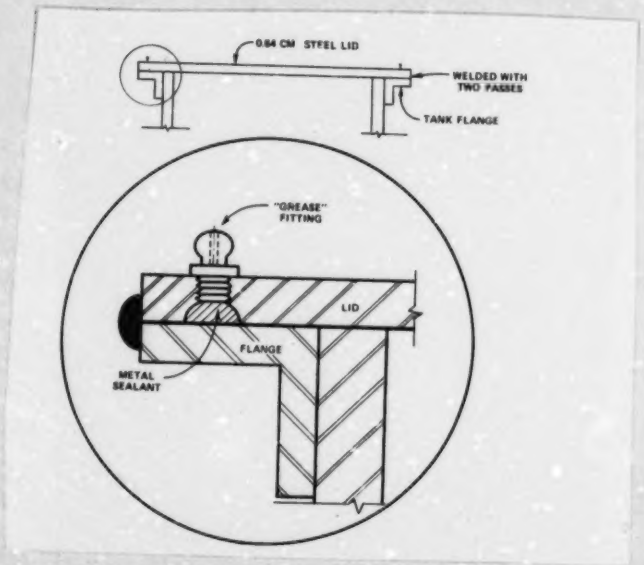

Figure 2. Detail showing method of sealing the tops of the test cells.

The carefully weighed loads of MSW were placed upon a 30.5 cm layer of a clayey-sandy soil which rested upon an approximately 3 cm-thick layer of polypropylene beads (6.25 mm dia.) as shown in Figure 1. The volume of compacted MSW in the small cells was 0.79 cu m (0.91 dia. x 1.22 m height) while the larger cells contained 6.42 cu m of compacted MSW (1.83 m dia. x 2.44 m height). Unbaled, unshredded MSW was placed in 30.5 cm lifts and compacted to approximately 400 kg (wet wt)/cu m density in the larger test cells. Randomly-sized lifts were compacted to an approximate density of 405 kg (wet wt)/cu m in the smaller cells. The actual weights of the MSW placed in each test cell are listed in Table 1. All MSW was obtained from non-commercial collection routes in Warren County, MS. A 500-kg, composite sample of the MSW was sorted at the time the test cells were being loaded. The MSW used was similar to that used in other studies, as can be seen in Table 2. Major differences are seen in the low levels of food and garden waste (perhaps due to dry weight basis of measurements) and in the high level of ash, dirt and fines. The high level of fines is thought to be caused by the pulverization of the glass fraction during the mixing process by the bull- dozer. It is not believed that these differences would have major effect upon the rate or composition of gases produced as the primary source of carbon is the paper fraction which is comparable to the earlier studies.

A 7.6-cm thick layer of washed pea gravel was placed in the head space of the test cells to help spread and disperse the applied leaching fluid over the surface of the MSW charge. A perforated, diffusion pan was bolted to the inside of the test cell top also to aid in dispersion of the leachant over the top of the MSW. A total of about 23 cm of head space in the small test

TABLE 1. TEST CELL SIZES AND LOADING

Parameter	Test Cell			
	#10	#22	#15	#16
Inside diameter (m)	0.91	0.91	1.83	1.83
Height (m)	1.83	1.83	3.66	3.66
MSW Wet weight (kg)	322.	318	2555.	2555.
Dry weight (kg)	264	261	2096	2096
Height of Waste (m)	1.22	1.22	2.44	2.44
MSW density (kg/cu m)	405	405	400	400
Volume of water added weekly (l)	8.3	8.3	33.4	33.4
Surface Area (sq m)	0.65	0.65	2.63	2.63

TABLE 2. PERCENT COMPOSITION OF MSW USED IN THIS AND OTHER STUDIES.

Category	This Study	Chian & et al. (1977)	Eifert & et al. (1977)	Jackson & Streng (1976)	Rovers & Farquhar (1973)
Paper	44.8*	36.5*	49.6**	40.5**	33.2**
Metal	10.8	14.7	9.5	8.2	7.4
Plastic, rubber, leather	9.0	2.8	6.0	6.5	3.6
Glass	7.6	6.8	12.0	7.4	9.5
Textiles, cloth	3.1	0.7	3.2	4.2	2.7
Disposable diapers	2.7	---	1.4	1.8	---
Food, garden waste	1.3	17.5	11.9	22.8	32.9
Wood	0.5	---	1.1	0.9	3.5
Ash, dirt, fines	20.1	14.9	5.4	5.5	6.4

* Percentages on dry weight basis.
** Percentages on wet weight basis.

cells and 84 cm of head space in the large test cells was left between the MSW and the test cell top plate (Figure 1).

After the test cells were loaded and all monitoring devices had been tested, the test cells were sealed by welding the steel lids to the cell tops and by pumping metal sealant (3M Weatherban 202; product of 3M Corp. Minneapolis, MN) into a machined groove (Figure 2) on the undersides of the lids. The details of the loading procedures for these four MSW test cells, the provisions for rainfall simulation and leachate collection, and the temperature and barometric pressure instrumentation are described in Myers and others (1979) and Shafer and others (1981).

The test cells were housed in a large facility where they stood in a concrete pit as shown in Figure 3. The pit, which was 1.5 m deep, allowed easy access to the tops of the tanks for servicing. The building was temperature controlled at 25°C ± 3°.

The test cell profiles were designed and constructed to simulate 1- and 2-m thick cylinders of MSW taken from a municipal landfill. The test cells resemble medium density cells in a sanitary landfill containing unprocessed wastes in the humid, eastern United States. An average rainfall of 132 cm (52 in/yr) with half of the precipitation infiltrating was assumed so that 66 cm of deionized water was added per year (at a rate of 1.27 cm per week). The input water was maintained at a pH of approximately 6.3 and greater than 3-megohm resistance. The initial moisture content of the MSW was 21.9% of its dry weight. Cell 22 was accidentally flooded on day 1053 when a valve

stem sheared off; excess water was drained immediately and data was taken throughout the rest of the experiment without further mishap.

GAS FLOW MEASURING AND SAMPLING SYSTEMS

The gas flow measuring and sampling systems consisted of gas probes in each tank that collected the gas produced by the decaying waste, a gas flow measuring and logging device, and a system that allowed the extraction of an uncontaminated gas sample for analysis. A schematic diagram of the system is shown in Figure 4.

Gas Probes

Three gas probes were installed in each test cell. Their locations within the MSW profile for a larger test cell are shown in Figure 5. Comparable locations were used in the small test cells. Each gas probe (Figure 6) consisted of a perforated 0.6-cm copper tube coated both inside and out with coal-tar epoxy to prevent corrosion by the leachate. The copper tubing was fitted into a perforated 1.9 cm polyvinyl chloride (PVC) pipe to protect the tubing during compaction of the waste. Each gas probe was connected to the gas collection line by a gas-tight union after the underlying municipal solid waste had been placed and compacted. An epoxy-sealed rubber insert in the PVC pipe upstream from the union prevented leachate contact with and possible corrosion of the union and the attached copper gas lines. A 1.9-cm PVC pipe attached to the inside wall of the steel tank covers the

Figure 3. Facility for housing a landfill simulator project.

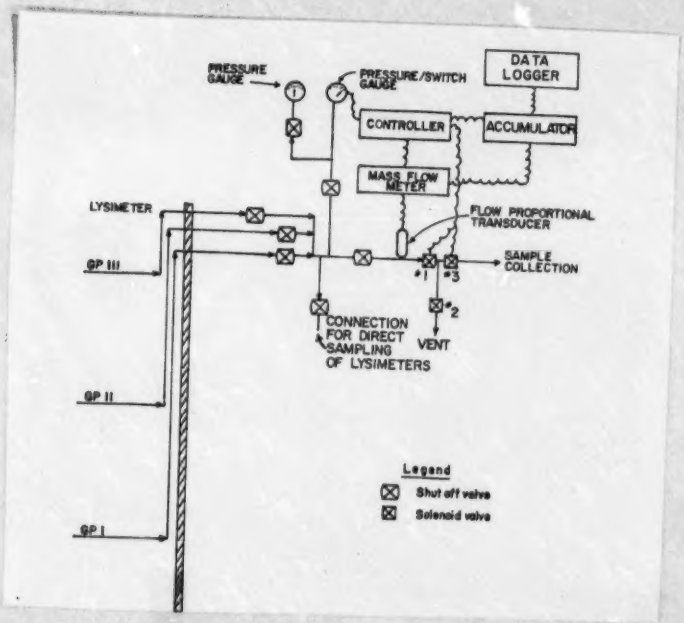

Figure 4. Schematic diagram of gas flow measurement and sampling system. GP = Gas Collection Probe.

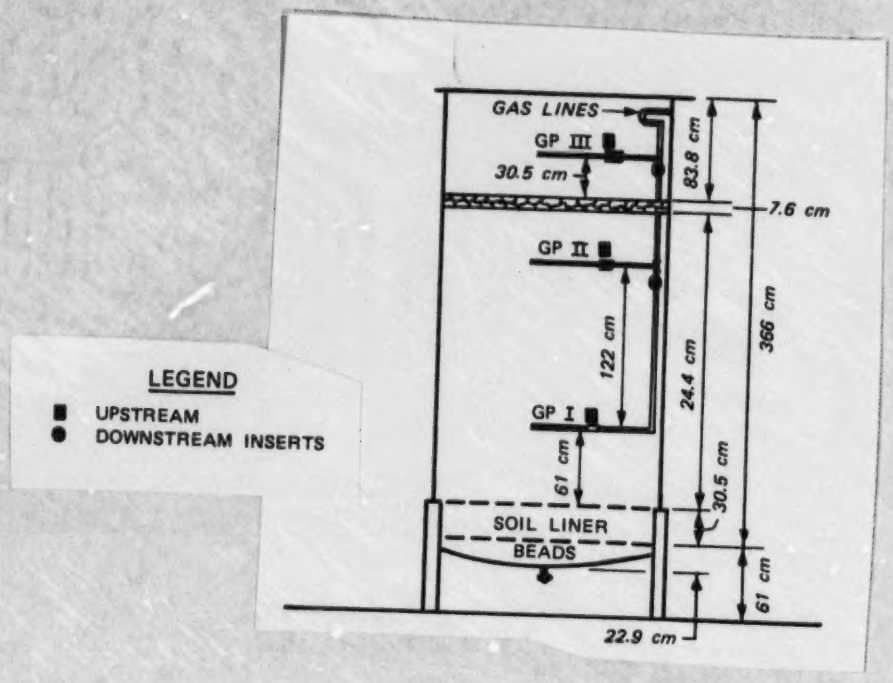

Figure 5. Position of gas collection probes in the large test cells.

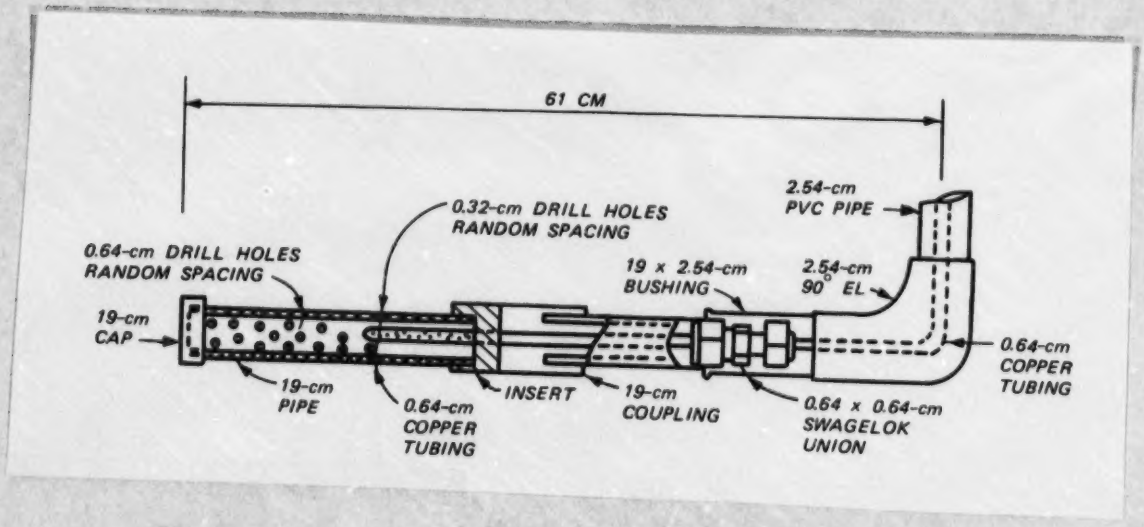

Figure 6. Detail of construction of gas collection probes.

gas lines as they extended up the wall and above the MSW. The copper gas collection lines pass through the tank wall at a point just below the top of the test cell. The PVC pipe and copper gas lines extending up the insides of the cells were attached in such a way to allow for compaction and consolidation of the municipal solid waste during the course of the experiment.

Gas Flow Measuring System

The gas flow measuring system operates using a pressure-controlled flow. Internal cell pressure is maintained at a pressure slightly above atmospheric by controlled out-gassing of the test cells. Gas flow is measured by a linear mass flowmeter. The internal tank pressure is normally allowed to reach a pressure of four-cm of water with respect to external atmospheric pressure; then gas is bled-off through the gas flowmeter until pressure is reduced to a low set point (usually two cm of water). The components of the gas flow measuring system for each cell are as follows: One differential pressure switch/gauge, three solenoid valves (normally closed), one linear mass gas flowmeter, one controller, seven shut-off valves, and one pressure gauge. A data logger was used to record gas production data from all four test cells.

The differential pressure switch/gauge incorporates gauge and switch set-point indicators for continuous indication of the internal pressure and switch settings. These units are diaphram-operated with switching accomplished by photocell-controlled relays. Set points are adjustable over a range of 0 to 5 cm of water. The unit can be regulated to 0.1 cm of water.

The pressure switch/gauge is used to operate two normally-closed solenoid valves. When the pressure reaches the high set point (0.4 cm of water), the two solenoid valves open and the gas from the test cell passes through the flowmeter. When the pressure drops to the low set point (two cm of water), the solenoid valves close. A pressure gauge (no switching capability) is installed so that periodic checks can be made on the pressure switch/gauge's performance. The pressure switch/gauge is a Dywer Photohelic Model 3000-5-CM and the auxiliary pressure gauge is a Dywer Magnehelic Model 2015 (Dywer Instruments, Inc. Michigan City, IN).

The linear, mass flowmeter consists of an electrically-heated tube and an arrangement of thermocouples which measure differential cooling caused by the gas passing through the tube. The thermoelectric elements generate DC voltages which are directly proportional to the rate of mass flow of gas through the tube. This proportionality permits the linear mass flowmeter calibrated for one gas to be used to measure the flow of a mixture of gasses, such as landfill gas, if the gas composition and the thermal conductivity of the component gasses are known. The mass flowmeter signal is insensitive to ambient pressure and temperature changes. These mass flowmeters, because of their linear response, are ideal for use with totalizers and automatic data reduction equipment. The flowmeter, at its maximum flow rate (1 liter/min), generates a 5 VDC output. The flowmeters are Matheson Model 8116-0113 with Model H-1K transducers (available from Matheson Corp. East Rutherford, NJ). The manufacturer's calibration was checked by comparing the recorded flow through each flowmeter with a reference flow standard (RFS). Where units

varied more than 0.5% from the RFS, they were recalibrated according to the manufacturer's instruction. The flowmeter remained on at all times.

Three, normally-closed and fail-closed, solenoid valves downstream from the linear mass flowmeter open and close the gas lines. The valves are energized by a controller accepting input from the pressure switch/gauge and the mass flowmeter. Additional manually-operated shut-off and switching valves can be used to selectively sample different locations in the test cells and to close off the gas flow from the test cell in the event maintenance is required.

The controller, a solid-state logic device, operates the solenoid valves as follows: First, when the pressure reaches the high set-point on the pressure switch/gauge, solenoid valves numbers 1 and 2 (see Figure 4) open and gas moves out of the test cell through the flowmeter. Second, when and if the flow rate reaches 95% of the measuring capacity of the flowmeter, solenoid valve Number 2 closes to keep the gas flow rate in a measurable range. Third, when the flow rate drops to 20% of the capacity of the flowmeter, solenoid Number 2 reopens. The second and third step prevent gas flow rates from overranging the flowmeter. And fourth, solenoids 1 and 2 are activated until the pressure drops to the low set-point of the pressure switch/gauge; if the pressure drops below the low set point both selenoids close.

Analog signals from the linear mass flowmeter are digitalized through a voltage to frequency conversion and then tallied in an electronic counter. Totals from the electronic counters (totalizers) are recorded on cassette

tape at hourly intervals by a 56-channel, Martek DLS data logger (available from Martek Corp., Newport Beach, CA). The counter registers are returned to zero after each hourly update. With each update the data logger also records the day, hour (from an internal clock), temperatures from three thermistor locations in the large test cells and from one thermistor location in the two small test cells (Figure 1), barometric pressure, ambient air temperature from two locations in the test facility, and reference voltages for the electronics associated with temperature measurement. All recorded data are identified according to day and hour. The system was very reliable only one failure was noted when an electronics problem in a totalizer caused the loss of 10 days data on test cell #10 during the initial phases of the experiment.

Gas Sample Collection

Two different sampling methods were tested during the first 18 days of test cell operation, one system used flexible (plastic) gas bags, the second used stainless steel cylinders. Initially gas samples were composited into plastic gas bags from which they were sampled for analysis using glass gas bulbs filled using a diaphram pump. Gasses were composited in bags using a flow proportional sampling system operated by the electronic flow controller. For every 90 milliliters of gas registered on the flow counters, the controller closed solenoid #2 (Figure 4) directing 10 milliliters through solenoid #3 into a Tedlar bag. Tedlar bags of 2-mil thickness and 48-liter capacity were used. The glass gas bulbs were cylinders with O-ring (neoprene) sealed glass plungers that act as valves on each end. Polyvinyl chloride tubing was used as the gas line from the flexible gas bags to the

glass cylinders and from the glass cylinders to a diaphram pump. The gas bags were attached to the gas measuring system (GMS) so that the bags would be filled with gas composition over a given sampling interval.

The system using gas bags had to be abandoned due to diffusion of oxygen into the bags. The expected oxygen depletion in the gas samples was not observed and an exhaustive search for possible leaks in all parts of the system was made. A check of the ability of the bags to exclude oxygen showed appreciable permeation through them. Gas bags filled with helium showed an increasing oxygen content when analysed over a 24-hour period. This leakage could be due to permeation through the polymer material or to physical breaks in the bags as suppliers caution that the bags are delicate and easily damaged. Thus, a system was developed which did not include the flexible, plastic, gas collection bags.

The sampling system used throughout most of the study (from day 18 to the end of the experiment) used grab samples collected from the test cells through the GMS in glass gas collection bulbs using the same pumping procedure used before. Shortly after the change to the grab samples collection method, the O-rings on the gas bulbs began to leak necessitating the use of an all-metal system using a compressor and steel storage tank. A small vacuum pump/compressor and a stainless steel gas cylinder was developed. Copper tubing was used for the gas lines from the GMS to the sample cylinder. Stainless steel quick-disconnects with double-end, shut-off valves were employed throughout the system in order to prevent contamination during connection and disconnection of the gas lines. The sample cylinder (Matheson,

stainless steel, 150 ml capacity) was purged by pumping several volumes of test cell gas through the cylinder, one end of the cylinder then shut off, and the gas pumped into a pressure of 2.9 kg/sq cm. The pump, a fluorocarbon diaphram model, provided oil-free operation and contaminant- free pumping. After the all metal collection system was installed, the oxygen levels found were, at, or below detection limits (< 0.1%).

Gas Analysis

Gas samples were analyzed on a Perkin-Elmer, Sigma 3 (Perkin-Elmer Corp. Norwalk, CT) gas chromatograph (GC) for oxygen, hydrogen, nitrogen, carbon dioxide, methane and water vapor. The separation and quantification of these gasses was made using a 274 x 3.2 mm Carbosieve S column and a column temperature program from 30°C to 175°C with an helium carrier gas and thermal conductivity detector. The GC was calibrated using commercially prepared gas mixtures, and the results reported in volume percent. The analytical technique used does not distinguish between oxygen and argon so that the very low levels of oxygen found throughout the experiment are very likely due to traces of argon in the gas samples. The procedure used for analysis is given in Supelco (1976).

DATA REDUCTION AND PRESENTATION

The raw data tapes from the data logger were read by a Martek Model 421-DRS magnetic tape reader and printed on a paper tape printer. Another Martek Model 421-DRS magnetic tape reader was used to transfer the data from the

magnetic tape to a Hewlett-Packard Model 9830 computer (manufactured by Hewlett-Packard Corvallis, OR) through a Martek Model 421-12-DRS computer interfacing unit. The data is verified with the original paper tape printout before being further processed. The verified data are reorganized and stored in raw form on magnetic tapes in an array that allows for easy access and manipulation by the computer. The raw data is reduced by engineering units and corrected for the non-linear output from the thermistors and barometric pressure sensors, and for variations in gas composition.

Programs have been developed to present the final data in any of several forms. The computer performs data manipulations as needed obtaining the data from the reduced data tape file for each test cell. Computerized data handling and manipulation and storage is necessary for the use of such a data acquisition system. A complete description of the data reduction system has been published by Myers and others (1979).

CHAPTER 4

RESULTS

LEACHATE PRODUCTION RATES AND MSW MOISTURE RETENTION

The two test cell sizes were used to determine any effects of scale. The larger cells, which had twice the diameter of the small, contained approximately 8 times the weight of dry MSW solids (of Table 3) in the small cells, but received only 4 times as much leaching medium. The large cells therefore received about half as much leaching fluid per kg MSW (15.9 ml/kg MSW week) as the smaller cells (31.4 ml/kg MSW week). To produce a 1.27 cm percolation of leachant per week, 8.25 l/wk of deionized water was added to each small test cell and 33.4 l/wk to the large test cells. The amount of leachate collected from the four MSW-only test cells at each sampling time is shown in Table 4. The rates of leachate production remained relatively constant over the period of the experiment at about 28 l/month for the small and about 104 l/month for the large test cells even though there is considerable variation between the size of individual leachate samples.

The volume of leachant retained by the MSW in the test cells is also shown for each monthly sampling period in table 4. These data are calculated as the volume of leachant added less the volume of leachate produced, and as such do not include the volume of water introduced in the initial MSW loading

TABLE 3. COMPARISON OF AVERAGE WATER BALANCE VALUES FOR SMALL AND LARGE TEST CELLS

Parameter	Small Test Cells	Large Test Cells
Volume of MSW (m3)	0.79	6.34
Dry Weight MSW (kg)	262.5	2067.0
Moisture in MSW (l)	38.6	304.0
Leachate input (l/week)	8.26	33.4
Total Leachate Produced in 1510 days leaching:		
(l)	1207.0	4472.0
(l/kg dry MSW)	4.60	2.16
AVERAGE OVER 1ST 6 MONTHS OF CONSISTENT LEACHATE COLLECTION:		
Leachate Retained (l)	288±14	1388±95
Total moisture retained in MSW:		
(l/test cell)	326.0	1688.0
(l/kg dry MSW)	1.235	0.822
Days estimated to first leachate production	244±12	294±20

TABLE 4. LEACHATE VOLUMES PRODUCED AND RETAINED

Sampling Day	Leachate Produced (ℓ)				Moisture retained (ℓ/Kg dry MSW)			
	Small cells		Large cells		Small cells		Large cells	
	(10)	(22)	(15)	(16)	(10)	(22)	(15)	(16)
247	72.8	76.0	234.4	156.1	0.82	0.82	0.46	0.48
282	0.0	0.0	0.0	0.0	0.98	0.98	0.54	0.56
303	59.8	38.2	92.7	81.7	0.85	0.93	0.54	0.57
331	0.0	0.0	0.0	0.0	0.97	1.05	0.61	0.63
359	54.1	54.5	166.9	153.3	0.89	0.97	0.59	0.63
388	39.9	39.5	122.0	127.3	0.87	0.95	0.60	0.63
437	36.7	49.2	152.9	147.2	0.95	0.98	0.64	0.67
458	0.0	0.0	0.0	0.0	1.04	1.08	0.69	0.72
486	33.3	36.7	135.1	127.9	1.04	1.07	0.69	0.72
514	42.0	35.2	145.7	176.4	1.01	1.06	0.68	0.70
542	35.0	34.6	130.0	72.2	1.00	1.05	0.68	0.73
570	34.1	31.4	127.6	117.0	1.00	1.06	0.69	0.74
598	33.7	33.3	151.4	138.6	1.00	1.06	0.68	0.74
633	42.8	39.0	95.0	173.0	0.99	1.07	0.71	0.73
664	39.0	31.8	132.1	119.6	0.98	1.08	0.72	0.75
689	40.1	34.5	129.3	115.3	0.94	1.06	0.72	0.75
724	41.3	63.2	120.6	119.9	0.94	0.98	0.74	0.77
752	15.1	19.7	105.9	119.6	1.01	1.03	0.75	0.78
780	24.6	21.2	124.9	117.3	1.04	1.08	0.76	0.79
815	28.4	24.2	51.9	106.0	1.09	1.14	0.81	0.82
843	31.8	27.6	123.8	109.8	1.09	1.16	0.82	0.83
878	35.2	31.0	99.2	118.1	1.12	1.20	0.85	0.85
906	27.6	28.4	103.0	84.8	1.14	1.22	0.87	0.87
934	29.9	29.5	100.3	77.2	1.15	1.23	0.88	0.90
969	45.0	33.7	155.9	96.5	1.14	1.26	0.89	0.93
1053	86.3	132.5*	303.1	447.8	1.18	(1.14)	0.94	0.91
1150	20.6	65.1	252.4	251.0	1.54	(1.32)	1.04	1.01
1235	40.9	59.4	225.5	214.6	1.77	(1.48)	1.13	1.10
1328	47.4	38.5	224.9	248.4	2.00	(1.75)	1.24	1.20
1415	53.0	96.9	357.1	356.9	2.19	(1.78)	1.26	1.22
1510	51.2	67.7	275.8	330.9	2.42	(1.95)	1.35	1.28

* Cell 22 flooded on day 1053 when valve stem sheared; unknown amount of leachant added.

or unmeasured spillage and evaporation. Moisture in the original MSW is estimated to be 38 l for the small and 297 l for the large cells. The volume of leachant retained in the cells is quite uniform but tends to increase throughout the experiment especially after the first 8 to 12 months of leachate production.

Taking the average retained volumes for the 2nd to the seventh month of collection (for which very stable numbers are found), the initial volume of leachant retained in the test cells over this time period was 1235 ml/kg dry weight of MSW for the small cells and 822 ml/kg for the large test cells including the moisture added in the original MSW (14.7% of the dry weight or 147 ml/kg dry MSW). The saturated moisture content of the MSW which corresponds to its initial "field capacity" [as defined by Fenn and others (1975) and later used by Swartzbaugh and others (1978)] is 123.5% and 82.2% of the dry MSW solids. These moisture levels are in the range expected to produce maximum gas production (Chian et al, 1977).

The nearly 50% larger moisture content of the saturated MSW in the smaller cells seems too large to be caused simply by differences in edge effects or by differences in the depth of MSW in the test cells. The higher leachant addition rate per kg MSW in the small test cells could cause a difference in the biological activity or decomposition rates.

The number of days before leachate should appear at the bottom of the test cells can be calculated from the addition rate and the field capacity of the MSW in the cells. For the small test cells this calculates to a number

very close to that actually seen in the experiment (244 days compared to the 247 experimental days till the first collection was made). The appearance of leachate from the large test cells would be expected to be later since the leachant addition rate was half that of the smaller cells; however the lower field capacity of the MSW in the large cells offset the lower addition rates so that the calculated time to first leachate is only about 20% longer than from the small cells.

As the amount of water retained in the test cells (or field capacity) increased over the period of the experiment, the small test cells continued to have significantly higher saturated percent moistures when compared to the large cell MSW (233% to 147% of the MSW dry weight at the end of the study, respectively). These long term calculations are subject to error because the breakdown of the MSW over the 4 year leaching period would reduce the MSW mass, and evaporation and minor leakage or sampling error become compounded to become increasingly significant.

LEACHATE CHARACTERISTICS

Leachate pH

The pH values of leachates from all test cells were generally in the range of 5.0 to 5.8 as seen in Table 5 which shows the actual pH values for each sampling period in the experiment. Little difference is seen between the small and large test cells, although the large test cells consistently were about 0.5 pH units more basic, especially leachates from test cell 16.

TABLE 5. PH-VALUES FOR LEACHATES

Sampling Day	Small test cells		Large test cells	
	(10)	(22)	(15)	(16)
303	5.00	5.65	5.30	5.40
331	5.25	5.45	5.20	5.30
359	5.40	5.50	5.29	5.30
388	5.30	5.43	5.13	5.10
437	5.25	5.42	5.19	5.31
458	5.15	5.20	5.20	5.30
486	5.00	5.20	5.00	5.40
514	5.10	5.35	5.25	5.40
542	5.20	5.45	5.35	5.65
570	5.20	5.45	5.40	5.70
598	5.15	5.50	5.45	5.85
633	5.20	5.35	5.40	5.95
664	4.70	4.90	4.80	5.30
689	4.90	5.20	5.00	5.50
724	4.70	4.90	4.90	6.90
752	4.90	5.10	5.20	5.70
780	5.00	5.20	5.20	6.00
815	4.85	5.10	5.10	5.65
843	5.10	5.50	5.40	5.80
878	4.50	5.70	6.00	5.30
906	5.80	5.90	6.00	6.70
934	4.90	5.00	5.40	6.10
969	5.00	4.90	5.10	5.70
1053	5.30	5.30	5.30	5.60
1150	5.05	5.00	5.20	5.65
1235	5.30	5.00	5.50	7.00
1328	5.40	5.25	5.85	5.60
1415	5.50	5.25	5.90	5.60
1510	5.40	5.25	5.85	5.60
Mean*	5.12	5.28	5.34	5.70

NOTE: All values in standard units.

Leachate Conductivities

The conductivity values for the leachates from the MSW only test cells are displayed in a similar manner in Table 6. Conductivities represent a simple and reliable, but somewhat nonlinear, measure of the ionic strength (concentration of dissolved salts and other charged material) of the leachate. As typical of leaching studies (Jackson and Streng, 1976; Ham and Bookter, 1982), the conductivities of the leachates from all test cells are high in the early leachate samples but decrease over the experimental period.

A very pronounced difference is evident between the large and small test cells for the first few months of leachate collection; the conductivities of the small test cell leachates decrease more rapidly until they are consistently lower, ending at about half the levels of the large test cell throughout the last two years of the study. These relative conductivity values should be accurate indicators of the relative ionic strength of the leachates. The lower conductivities of the leachates from the smaller test cells may result from the higher leachant addition per kg dry MSW, although the conductivities of leachate from both test cells sizes is remarkable stable from about day 500 throughout the experiment. Also, excellent agreement is seen between test cells of comparable size (averaging within 3% overall).

Concentration of Constituents in Leachates

The levels of constituents found in the MSW-only test cell leachates are in line with those found in previous studies of landfill and MSW lysimeter leachates (Rovers and Farquhar, 1973; Jackson and Streng, 1976; Eifert et al,

TABLE 6. CONDUCTIVITY VALUES FOR LEACHATES

Sampling Day	Small test cells (10)	Small test cells (22)	Large test cells (15)	Large test cells (16)
247	12000	9500	5000	13000
303	9000	8700	9800	10000
331	4100	7100	8000	9400
359	10500	8500	8900	11000
388	9000	8000	8500	8500
437	6400	5900	7100	7900
458	7800	8500	7500	8500
486	6500	8500	8000	11000
514	6000	5000	8500	10000
542	5000	4800	8200	8500
570	3200	3200	5600	6400
598	4000	3500	6500	7500
633	3500	3500	6100	7200
664	3200	2800	5200	5800
689	3000	3100	5400	6600
724	2600	2500	6300	5900
752	2700	2700	5400	6100
780	2600	2500	5200	5600
815	3000	2600	6200	6900
843	3300	2800	7300	7400
878	3200	2900	4900	6700
906	2700	2800	6400	6400
934	2700	2400	6000	5200
969	2900	2900	6500	7200
1053	2500	2300	5600	5600
1150	3000	3000	5000	6000
1235	2300	2400	7000	6400
1328	2700	2100	6000	4900
1415	2700	2200	6000	4900
1510	2700	2100	6000	4900
Mean	4493	4293	6603	7380

NOTE: All values in μ mho/cm^2

1977; Ham and Bookter, 1982). Very high concentrations of chemical and biochemical oxygen demand, total organic carbon, and total volatile acids are found in all leachates. Patterns of constituent leaching also follows established form with high initial concentrations which decrease asymtotically over the length of the leaching period until the levels of most constituents at the end of the 4 year leaching period are down to about 1/4 to 1/3 of their initial values. Only iron shows values increasing to a broad peak and then leveling off late in the study. The iron (and perhaps manganese) is apparently being solubilized by bacterial reduction, the rate of which limits it's leachate concentrations.

The total mass of parameters leached per kg dry MSW loaded into the cells is shown in Table 7. From 0.5 to 2 grams per kg MSW of calcium, iron, potassium, sodium, and chloride have been lost from all cells. Ten or more mg/kg MSW of boron, magnesium, manganese, and zinc have been leached from the MSW. Twenty five to 70 grams of chemical oxygen demand have appeared in the leachate per kg of MSW loaded into the cells. The leachates are also high in organic nitrogen lost.

Of the metals asseyed, a total mass of 1 to 3 kg of calcium, iron, potassium and sodium has been leached from the large test cells; also lost in gram quantities are boron (over 10 g), manganese (over 30 g) and zinc (25 g). About 2 kg of chloride and organic nitrogen (TKN) have been found in the leachates.

TABLE 7. TOTAL MASS OF PARAMETERS LEACHED PER KG DRY MSW FROM TEST CELL OVER 1510 DAYS OF LEACHING

Parameter	Small cells		Large cells	
	(10)	(22)	(15)	(16)
Oxygen Demand:				
Chemical	75.3	65.4	50.1	51.9
Biochemical	56.2	44.8	26.6	32.1
Total Organic Carbon	19.5	14.6	12.2	12.0
Alkalinity	6.5	6.7	5.3	6.0
Calcium	2.8	2.2	1.3	1.0
Iron	2.0	1.6	1.0	1.1
Magnesium	0.36	0.26	0.23	0.23
Manganese	0.040	0.028	0.026	0.019
Potassium	1.3	1.2	0.88	0.94
Sodium	1.6	1.1	1.2	1.2
Zinc	0.067	0.017	0.015	0.006
Boron	0.012	0.014	0.006	0.007
Chloride	1.4	0.95	1.2	1.4
Total Kjeldal Nitrogen	1.7	1.6	1.4	1.4
Total Phosphate	0.11	-	0.05	-

NOTE: All values in grams leached/kg dry MSW.

Total Organic Carbon

Appreciable amounts of organic carbon have been lost as dissolved organic compounds (TOC) in the leachates. Over 4 kg (15 g/kg dry MSW) of organic carbon was leached from the small and 15 to 18 kg (7 to 8 g/kg dry MSW) from the large test cells; this is about 1% of the original MSW dry weight loaded into the test cells. If the MSW is assumed to consist of about 20% organic carbon (Chian and DeWalle, 1976) then between 4 and 7.5% of the organic carbon originally loaded into the test cells has been leached. Both small and large test cells lost an average of 4.5 to 4.7 g of TOC per liter of leachate produced over the entire experiment.

Total organic carbon (TOC) levels in the leachates follows patterns similar to those of leachate conductivities discussed above. TOC levels have high initial values which rapidly drop to lower, relatively stable levels after two or three years of leaching. Early samples from the large test cells appear to be similar to, or even lower than, those from the smaller test cells. However, the large test cells produce leachates having consistently higher TOC concentrations after a year or two of leaching. The TOC levels average 76% higher in leachates from the larger test cells probably reflect the same cause as the higher conductivities, that is, a lower dilution rate due to the lower volumes of leachate added per kg dry MSW solids in the larger cells. The lower leachate volumes per unit dry MSW produced in the large cells means that the leachate which is produced will tend to be stronger.

Chemical (COD) and Biochemical (BOD) Oxygen Demand

The large organic carbon load in the MSW leachates is also evident in the large chemical and biochemical oxygen demands (COD and BOD) of the leachates. The overall mean oxygen requirements of leachate are about 15 g/l chemical oxygen demand and 12 g/l biochemical oxygen demand for both the small and the large test cells. The overall ratio of COD to TOC is near 3.0 as is typical of such wastes (Chian and DeWalle, 1976) (3 mg of oxygen is required for each mg of organic carbon contained in the leachates). This value is slightly higher than would be expected for organic carbon loads consisting mainly of organic acids and fermentation fragments which produce COD to TOC ratios in the range of 2.0 to 3.0. The additional oxygen requirement reflects levels of reduced iron, and perhaps the presence of reduced nitrogen and sulfur species.

OVERALL GAS PRODUCTION RATES

Gas production from the test cells was very rapid at first, but soon dropped to more stable rates. In the early part of the study, gas was released irregularly throughout the day rather than at consistent rates. This is illustrated in Figure 7 which shows the relative hourly rates for day 18 from large, test cell, #15. Also shown are the temperature and barometric pressure reading for the same time period. Figure 8 shows similar data for the same test cell after 80 days when gas production had slowed considerably. The plot also shows the effect of temperature on the evolution of gas (day 80 was July 5). Note that the lower and middle thermistor temperatures are quite stable as they are embedded in the waste material; however,

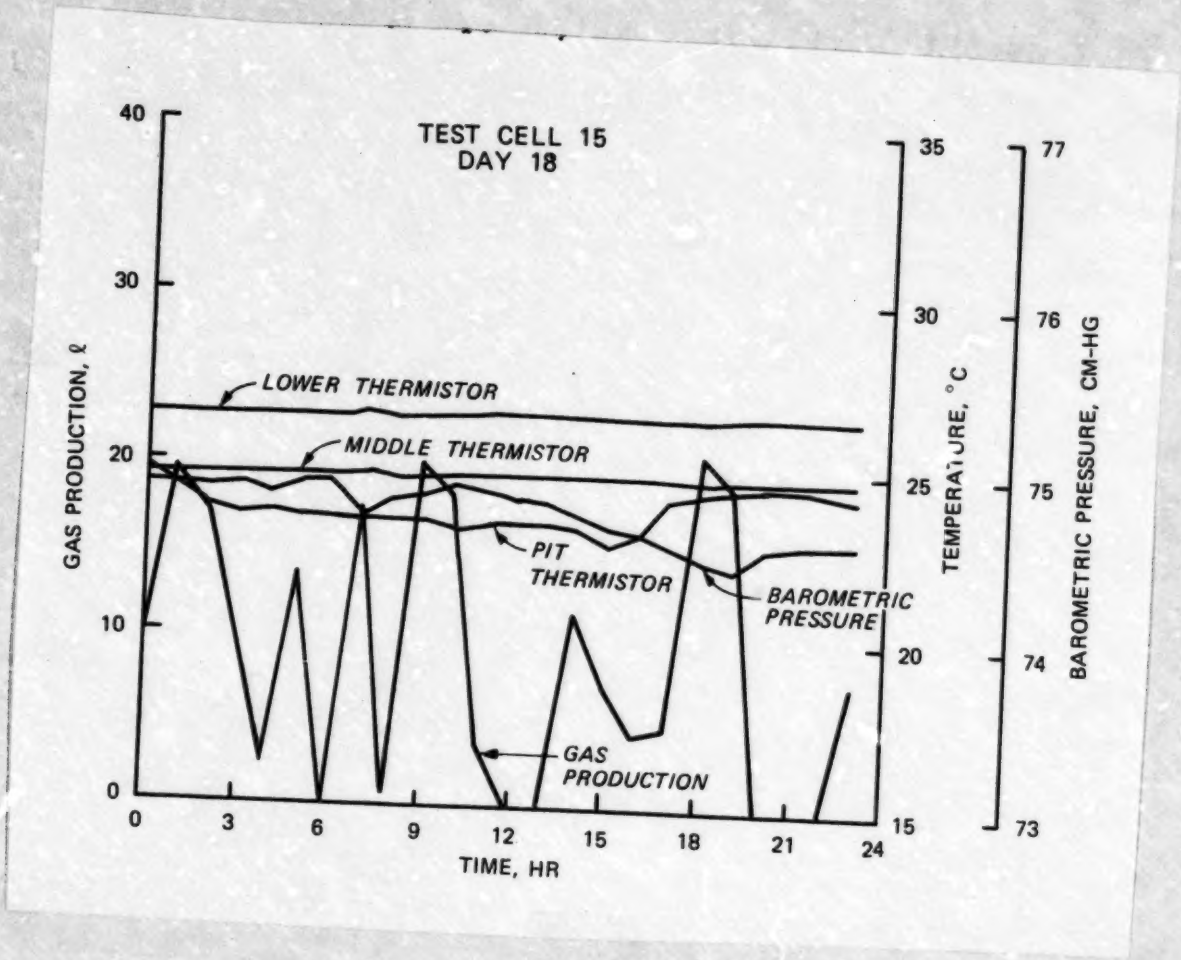

Figure 7. Temperature, barometric pressure, and gas flow for day 18, test cell #15.

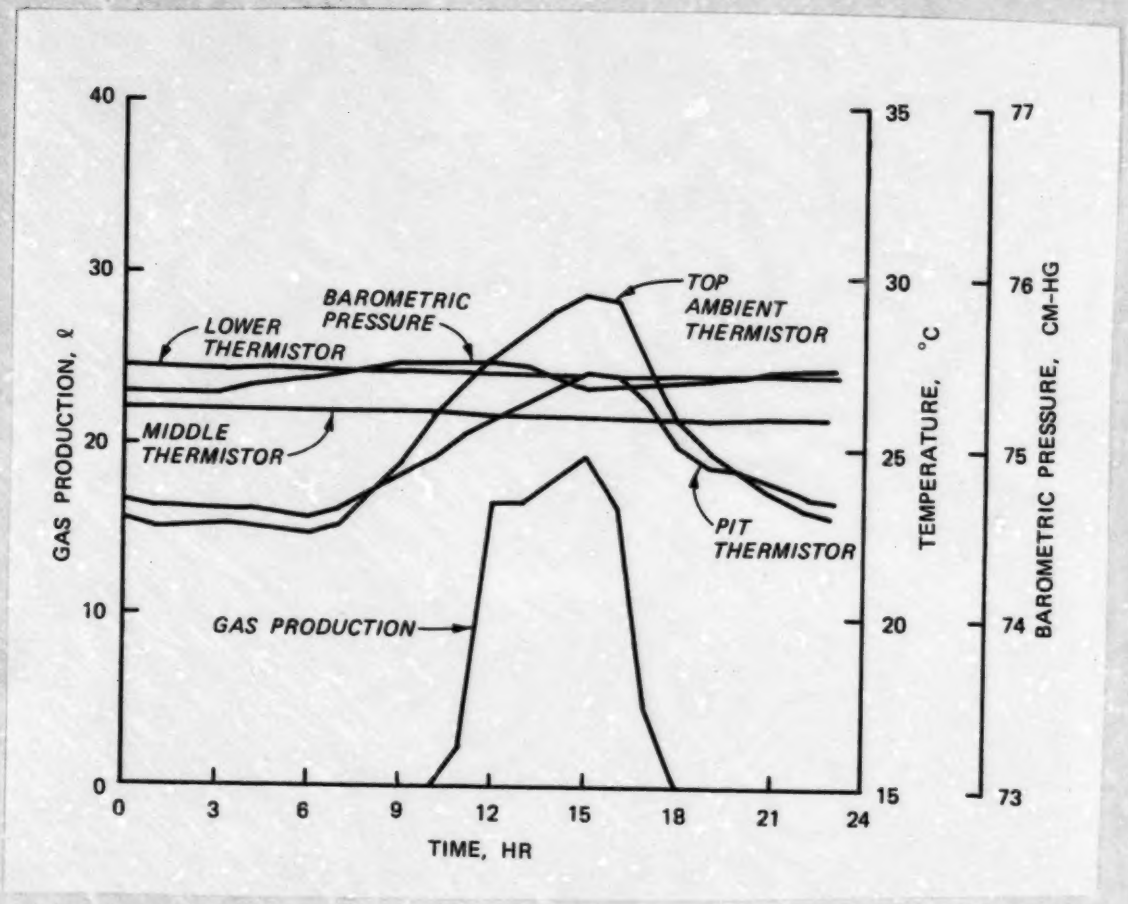

Figure 8. Temperature, barometric pressure, and gas flow for day 80, test cell #15.

the top thermistor which measures the temperature of the gas space above the waste varies considerably on this hot, summer day. It follows the "pit," or outside temperature which is taken near the bottom of the test cell. As the temperature in the head space increases, the gas expands so that its release takes place predominantly during the afternoon hours as shown. This pattern was quite typical for all of the test cells throughout the experiment. The rate of gas evolution decreased as the experiment progressed and gas would typically be released only every four or five days, often being released during periods of decreasing barometric pressure.

In order to compensate for the irratic pattern of the gas release and to give an accurate representation of the results, data illustrating the amounts of the gases produced per day have been summed, then averaged, over 14-day periods and are listed in the tables with the median day of the two week period. The actual, total amount of gas released per day from each of the four test cells for the first 630 days of the experiment is listed in Table 8 and plotted for the large and small test cells respectively in Figures 9 and 10. In both figures the high initial rate of gas production is followed by a rapid drop during the first days after the cells were sealed. The data for the small test cells (Figure 10) is more erratic as might be expected for their eight-times smaller volume, but they follow an identical pattern. Nearly 3000 l of gas were released from the small test cells during this time and 26,000 l from the large cells. Very close to 1/2 of this gas was released in the first 100 days when gas production was very high.

TABLE 8. VOLUME OF GAS PRODUCED PER DAY FROM TEST CELLS OVER TWO WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	34.15	26.31	244.70	275.81
21	27.67	27.03	163.59	181.64
35	5.82	21.62	120.19	126.52
49	12.14	18.59	114.16	112.82
63	8.52	10.06	127.51	125.11
77	5.95	2.39	116.02	114.48
91	7.92	0.41	88.15	98.48
105	9.64	16.03	94.02	92.07
119	9.02	24.71	82.69	80.03
133	7.74	1.65	84.20	81.89
147	7.49	2.69	71.41	67.39
161	3.20	2.51	46.37	42.76
175	4.64	2.83	48.93	39.87
189	1.17	2.38	27.83	28.00
203	6.01	3.16	36.99	33.79
217	5.12	3.23	32.08	29.64
231	3.33	2.03	22.51	21.00
245	2.75	1.62	15.40	14.09
259	2.38	1.33	8.65	8.18
273	2.42	B	10.96	10.29
287	1.23	B	7.47	7.05
301	3.26	2.13	10.03	8.69
315	1.25	0.17	7.10	6.73
329	1.69	1.77	9.38	9.05
343	2.08	2.70	18.14	17.23
357	2.27	1.76	22.86	21.41
371	0.60	0.10	19.83	18.73
385	3.34	2.78	18.10	19.90
399	0.09	0.16	10.32	9.71
413	4.44	5.53	31.94	30.51
427	2.91	3.08	17.38	16.72
441	2.33	2.10	25.39	22.10
455	0.65	1.11	6.89	5.80
469	2.08	0.90	9.34	8.93
483	3.48	3.00	25.10	24.11
497	0.85	0.54	7.87	7.54
511	1.52	0.07	9.95	10.47
525	1.28	1.12	9.13	8.26
539	0.11	0.18	1.81	0.11
553	0.16	0.13	0.15	0.14
567	0.73	B	0.12	0.11
581	1.49	0.11	2.71	2.46
595	1.14	0.17	9.60	8.94
609	0.92	0.52	2.45	2.32
623	1.58	N	7.00	6.67

NOTE: All values in l/day. N = no data; B = no gas detected.

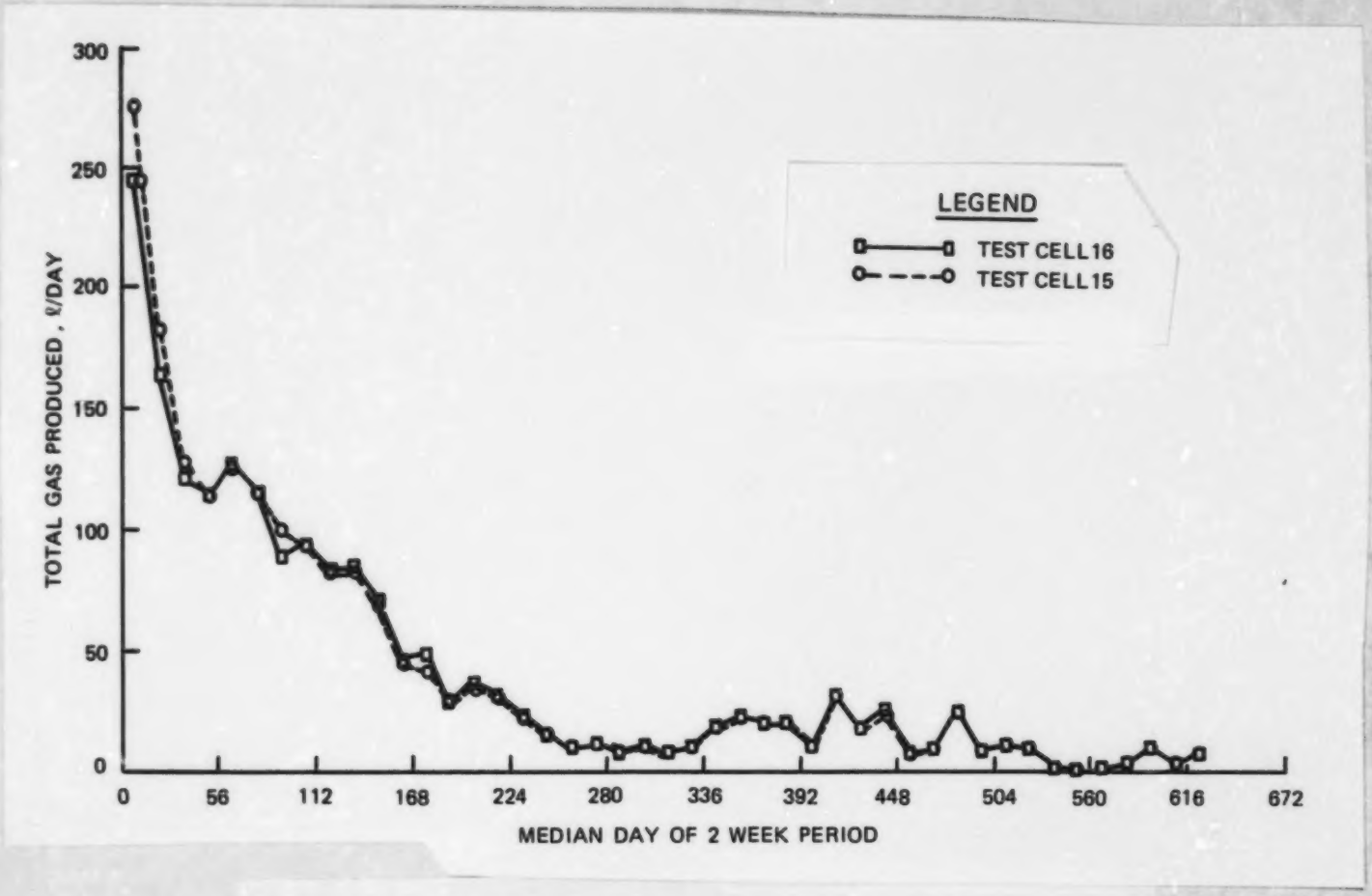

Figure 9. Total gas produced by large test cells summed over 14-day periods.

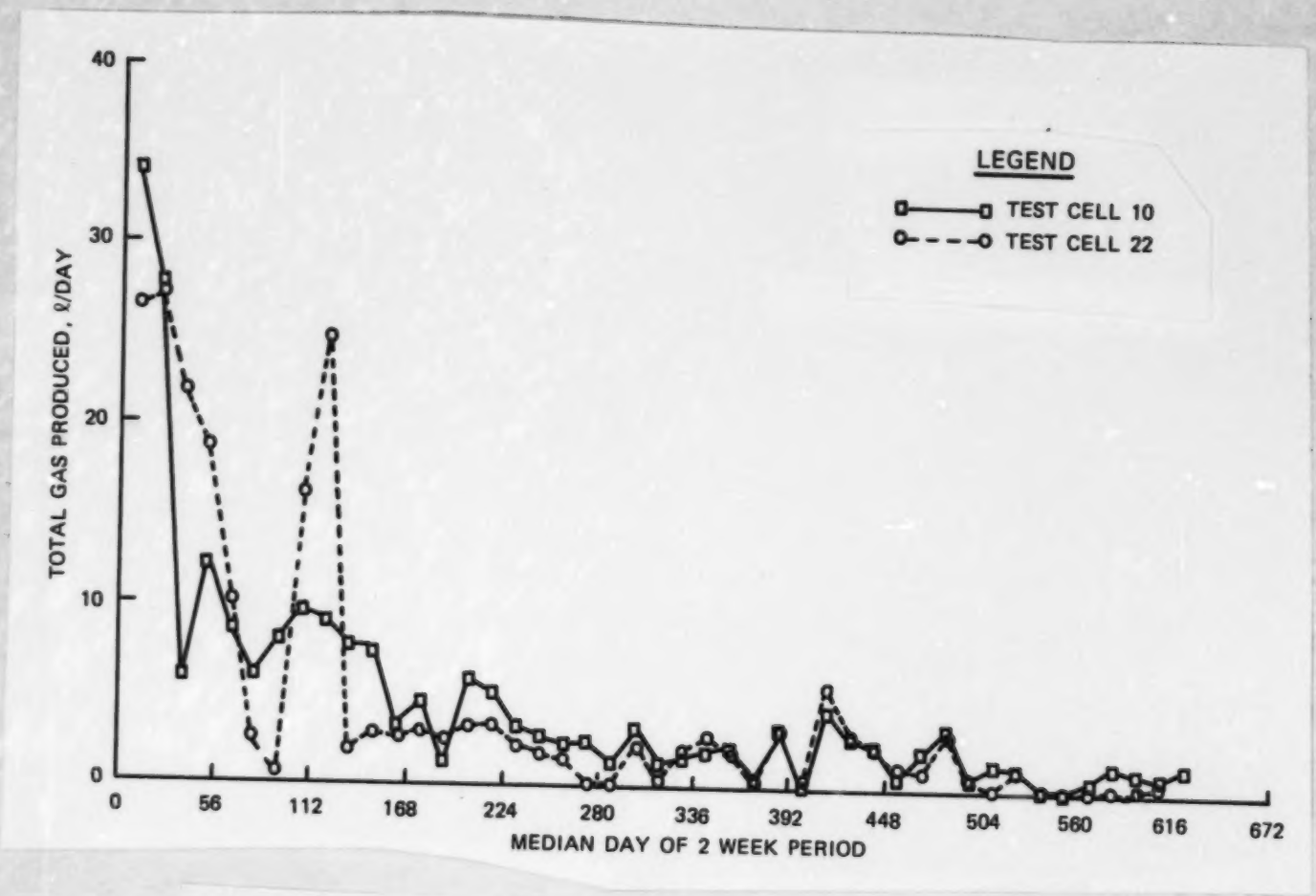

Figure 10. Total gas produced by small test cells summed over 14-day periods.

As can be seen in Table 9, the amount of gas produced per kg dry weight of MSW loaded into the cells per day is nearly the same for both test cell sizes, averaging less than 20% more for the larger test cells. The overall average gas production for all four cells is 18.9 ml per kg dry wt MSW per day over the 630 day period shown in the table. The average for the first 100 days only was 61.8 ml/kg dry wt MSW.

An appreciable rise in the gas production from day 350 to about day 500 is apparent in Figures 9 and 10. This is believed to due to the higher temperatures in the building during the summer (April to September). The lower rates gas production rates before and after this period coincide with the colder winter temperatures. Even though the large building was temperature-regulated, a 3 to 6 degrees Celcius difference between summer and winter could not be avoided.

GAS COMPOSITION

The relative composition of the gases produced, as well as the total amounts, followed closely the pattern proposed by Farquhar and Rovers (1973). In general, oxygen was very rapidly depleted and swept out of the cells; nitrogen levels also dropped rapidly to low but fairly stable levels. Carbon dioxide levels rose rapidly to become the predominant gas throughout the length of the experiment in all test cells. Hydrogen typically appeared before the onset of methane production and rapidly declined as methane production increased. This change in gas composition is due most likely to the use of the hydrogen by methanogenic bacteria to reduce carbon dioxide to methane (McCarty, 1964).

TABLE 9. VOLUME OF GAS PRODUCED PER KG DRY MSW DAY FOR TEST CELLS OVER TWO WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#16	#15
7	129.36	100.84	116.75	131.63
21	104.83	103.58	78.05	86.64
35	22.06	82.86	57.34	60.37
49	46.01	71.25	54.47	53.83
63	32.30	38.56	60.84	59.69
77	22.54	9.19	55.35	54.62
91	30.01	1.60	42.06	46.99
105	36.52	61.42	44.86	43.93
119	34.19	94.69	39.46	38.18
133	29.32	6.35	40.17	39.07
147	28.40	10.31	34.07	32.16
161	12.15	9.64	22.12	20.40
175	17.61	10.88	23.35	19.02
189	4.46	9.15	13.28	13.36
203	22.79	12.13	17.65	16.13
217	19.41	12.41	15.31	14.14
231	12.64	7.79	10.74	10.02
245	10.44	6.22	7.35	6.72
259	9.02	5.10	4.13	3.91
273	9.19	B	5.23	4.91
287	4.66	B	3.57	3.37
301	12.37	8.17	4.79	4.15
315	4.77	0.68	3.39	3.21
329	6.43	6.78	4.48	4.32
343	7.89	10.36	8.66	8.22
357	8.63	6.76	10.91	10.22
371	2.28	0.40	9.46	8.94
385	12.66	10.68	8.64	9.49
399	0.34	0.62	4.93	4.63
413	16.83	21.22	15.24	14.56
427	11.03	11.81	8.29	7.98
441	8.85	8.08	12.12	10.55
455	2.46	4.29	3.29	2.77
469	7.91	3.48	4.46	4.26
483	13.21	11.53	11.98	11.50
497	3.24	2.10	3.76	3.60
511	5.78	0.30	4.75	5.00
525	4.86	4.31	4.36	3.94
539	0.44	0.70	0.87	0.06
553	0.61	0.52	0.07	0.07
567	2.80	0.00	0.06	0.05
581	5.65	0.45	1.30	1.18
595	4.33	0.68	4.58	4.27
609	3.51	2.01	1.17	1.11
623	6.00	N	3.34	3.19

NOTE: All values in ml/kg dry MSW day. N = no data; B = no gas detected.

Each of the gases is discussed individually from the aspect of total amount of the gas released over the first 630 days for which volumetric data was taken and as a percentage of the total gas produced over the 1500 day length of the experiment. Gas analyses were made at approximately 30 day intervals from spot samples taken from the head space of the test cells.

Oxygen

The amount of oxygen present in gas released from the test cells decreased rapidly as seen in Table 10. The proportion of oxygen in the gas released is shown as a percent in Table 11. The relatively high percentages of oxygen up to day 18 are believed to be due to oxygen leakage (probably by diffusion) into the flexible plastic gas collection bags used early in the project. After the stainless steel gas collection cylinders were installed (from day 18 on) the oxygen concentrations maintained a low and consistent level. These low oxygen values throughout the bulk of the experiment include an unknown percentage of argon gas which is not separated from oxygen in the gas chromatographs. Oxygen and argon appear as one peak in the gas analysis procedure. Argon was used to purge the collection apparatus to maintain anoxic conditions. Oxygen contamination of the test cells or sampling system during the experiment was not a problem.

Carbon Dioxide

By the second day of gas collection, carbon dioxide was the major component in the released gases and it remained so throughout the length of the study. Table 12 shows the total volume of carbon dioxide released during each

TABLE 10. VOLUME OF OXYGEN AND/OR ARGON* PRODUCED PER DAY IN TEST CELLS OVER TWO WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	0.5666	0.1558	3.6567	4.0953
21	0.1855	1.0963	2.2037	3.0527
35	0.0853	0.0068	0.1759	0.2989
49	0.0065	0.0024	1.2343	0.1450
63	0.0138	0.0096	0.6798	0.3753
77	0.0311	0.0033	0.1605	0.1525
91	0.0490	0.0012	0.4117	0.0984
105	0.1824	0.0583	0.5544	0.0940
119	0.5506	0.0716	0.1654	0.0880
133	0.1823	0.0053	0.2716	0.1062
147	0.0246	0.0101	0.2311	0.0898
161	0.0064	0.0100	N	0.0427
175	0.0067	0.0105	0.0933	0.0378
189	0.0015	0.0081	0.1054	0.0507
203	0.0102	0.0107	0.1368	0.0676
217	0.0185	0.0106	0.1261	0.0401
231	0.0203	0.0063	0.0945	0.0130
245	0.0168	0.0050	0.0646	0.0087
259	0.0104	0.0045	0.0441	0.0106
273	0.0106	B	0.0559	0.0133
287	0.0054	B	0.0381	0.0091
301	0.0065	0.0384	0.0401	0.0086
315	0.0025	0.0032	0.0284	0.0067
329	0.0033	0.0053	0.0281	B
343	0.0041	0.0081	0.0544	B
357	0.0227	0.0052	0.0685	0.0133
371	0.0090	0.0003	0.0595	0.0187
385	0.0397	0.0073	0.1331	0.0124
399	0.0003	0.0003	0.1342	B
413	0.0142	0.0110	0.1348	0.0974
427	0.0087	0.0061	0.0347	0.0669
441	0.0070	0.0042	0.0508	0.0884
455	0.0017	0.0022	0.0137	0.0231
469	0.0041	0.0018	0.0186	0.0268
483	0.0069	0.0060	0.0502	0.0723
497	0.0017	0.0011	0.0157	0.0226
511	0.0039	0.0001	0.0199	0.0179
525	0.0038	0.0022	0.0182	0.0082
539	0.0003	0.0003	0.0036	0.0001
553	0.0003	0.0002	0.0003	B
567	0.0020	B	0.0001	0.0001
581	0.0044	0.0002	0.0027	0.0024
595	0.0040	0.0005	0.0604	0.0089
609	0.0037	0.0015	0.0344	0.0023
623	0.0067	N	0.0768	0.0149

NOTE: All values in l/day. N = no data; B = no gas detected.
* Oxygen and Argon not distinguished in analyses.

TABLE 11. PERCENT OF OXYGEN AND/OR ARGON* IN GAS FROM TEST CELLS.

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1	1.8	N	1.7	1.8
2	1.1	N	1.2	1.1
6	1.8	N	1.6	1.5
13	1.8	1.6	1.6	1.9
18	0.2	4.6	1.5	2.0
30	1.7	0.1	0.3	0.5
40	B	B	B	B
47	B	0.1	1.3	B
53	0.1	0.1	1.2	0.3
67	0.2	0.1	0.2	0.3
76	0.5	0.2	0.1	0.1
83	0.8	0.2	0.2	0.1
99	0.5	1.1	0.7	0.1
116	6.1	0.3	0.2	0.1
145	0.4	0.4	0.4	0.2
157	0.2	0.4	N	0.1
171	0.1	0.3	0.3	0.1
181	0.1	0.4	0.4	0.1
201	0.2	0.3	0.4	0.2
236	0.6	0.3	0.4	0.1
263	0.4	0.3	0.5	0.1
299	0.2	1.8	0.4	0.1
341	0.2	0.3	0.3	B
367	1.5	0.3	0.3	0.1
396	0.4	0.2	1.3	B
425	0.3	0.2	0.2	0.4
489	0.2	0.2	0.2	0.3
535	0.3	0.2	0.2	0.1
549	0.2	0.2	0.2	B
577	0.3	0.2	0.1	0.1
607	0.4	0.3	1.4	0.1
642	0.5	0.3	0.4	0.5
667	0.6	0.2	0.3	0.1
695	0.8	0.6	0.6	0.1
730	0.7	0.5	0.5	B
758	0.4	0.2	0.4	0.1
786	0.5	0.2	0.3	0.1
848	0.3	0.2	0.5	0.1
879	0.6	B	0.6	0.1
913	0.6	0.3	1.0	0.2
941	0.4	0.6	0.8	0.1
977	0.9	0.3	1.7	0.3
997	0.5	0.2	1.0	0.4

(Continued)

TABLE 11 (Concluded)

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1033	0.6	0.8	0.8	0.4
1063	0.5	0.4	0.9	0.2
1091	0.6	0.2	1.1	0.2
1152	0.3	B	0.5	B
1181	0.3	B	0.7	B
1218	0.4	B	0.6	0.4
1252	0.4	0.5	0.7	0.1
1287	0.6	B	0.9	0.3
1312	0.6	0.1	0.7	1.7
1330	0.7	0.1	0.7	1.4
1364	0.5	0.1	0.7	0.3
1420	1.6	1.6	1.6	0.5
1453	1.2	0.1	0.7	0.2
1489	N	1.9	0.5	0.6
1518	N	0.1	0.5	0.1

* Oxygen and argon not distinguished in analyses.

NOTE: N = no data; B = none detected.

two week period for the first 630 days of the experiment. Of the total gas evolved during this period, carbon dioxide represented between 67% and 76%. The proportion of carbon dioxide in the evolved gases for the full 1500 days is listed in Table 13 and shown diagrammatically in Figure 11. The values remain consistently high, especially in test cell 16 where they remain near 90%. The dramatic drop in carbon dioxide percentage from day 800 to about day 1100 in small test cell 15 is mirrored by a rise in nitrogen proportions from about 15% to over 60% during the same time period (and a decrease in methane production).

The amount of carbon dioxide per kg of dry MSW per day is calculated in Table 14 for the first 630 days of the study. The total amount released varied from 11.9 to 14.9 ml/kg MSW day in both the large and small test cells. The rates of carbon dioxide evolution dropped rapidly to a low level until about day 250 when the rate of decrease slowed, paralleling total gas production. This is about the time that hydrogen and methane were first produced, perhaps indicating that a more stable phase in microbial activity had been reached. The rates of carbon dioxide production still decreased after this time but at much lower, overall rates.

Hydrogen

Hydrogen gas production was expected to precede the production of methane (DeWalle, Chian and Hammerberg, 1978; Farquhar and Rovers, 1973; McCarty, 1964). Hydrogen was first seen in all test cells between 100 and 150 days after sealing. This was during the last of the major drops in overall gas

TABLE 12. CARBON DIOXIDE VOLUME PRODUCED PER DAY FOR TEST CELLS OVER TWO WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	18.56	6.23	135.03	149.14
21	20.07	16.52	112.31	112.04
35	4.15	19.16	88.04	86.47
49	10.58	16.31	82.65	80.78
63	7.45	9.01	96.44	96.81
77	5.00	2.04	90.19	90.50
91	6.05	0.32	67.54	80.65
105	6.81	11.80	70.29	78.47
119	5.82	17.91	59.37	68.58
133	6.16	1.18	56.00	67.44
147	6.56	1.88	37.69	55.01
161	2.77	1.78	N	37.11
175	4.09	1.98	20.22	34.58
189	1.04	1.71	17.33	23.94
203	5.48	2.28	22.93	28.69
217	4.56	2.36	20.81	25.32
231	2.88	1.52	15.35	18.06
245	2.37	1.21	10.50	12.11
259	2.00	0.93	6.03	7.05
273	2.04	B	7.64	8.87
287	1.03	B	5.20	6.08
301	2.70	1.45	7.28	7.44
315	1.04	0.12	5.15	5.76
329	1.41	1.29	7.16	8.18
343	1.74	1.98	13.86	15.58
357	1.74	1.30	17.28	19.47
371	0.43	0.07	14.89	17.10
385	2.44	2.08	13.55	18.24
399	0.06	0.12	7.70	8.96
413	3.46	4.26	25.10	27.45
427	2.27	2.37	13.83	14.95
441	1.82	1.62	20.21	19.76
455	0.51	0.87	5.48	5.19
469	1.66	0.78	7.64	8.31
483	2.77	2.60	20.53	22.42
497	0.68	0.47	6.44	7.01
511	1.22	0.06	8.17	9.87
525	1.03	0.88	7.52	7.85
539	0.09	0.14	1.49	0.11
553	0.12	0.10	0.12	0.14
567	0.54	B	0.10	0.10
581	1.08	0.09	2.23	2.33
595	0.83	0.13	7.63	8.47
609	0.67	0.40	1.85	2.20
623	1.14	N	5.41	6.29

NOTE: All values in 1/day. N = no data; B = none detected.

TABLE 13. PERCENT OF CARBON DIOXIDE IN GAS FROM TEST CELLS

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1	45.0	N	49.0	44.4
2	50.3	N	52.9	51.3
6	53.4	N	55.4	57.5
13	62.8	64.0	63.7	58.7
18	75.1	60.5	67.8	61.0
30	70.0	88.7	77.3	65.5
40	79.8	88.6	69.4	70.9
47	86.7	86.3	72.2	68.2
53	87.5	89.9	73.5	75.3
67	87.4	89.5	76.7	78.4
76	84.1	79.6	78.0	79.4
83	81.9	77.3	77.8	78.5
99	72.8	85.2	75.6	85.1
116	64.5	72.5	71.8	85.7
145	87.8	69.6	63.6	80.6
157	86.6	70.9	N	86.8
171	89.3	70.0	65.6	86.7
181	88.8	68.2	64.1	87.7
201	91.1	72.1	62.0	84.9
236	86.3	75.0	68.2	86.0
263	84.3	70.3	69.7	86.2
299	82.7	68.1	72.6	85.6
341	83.6	73.4	76.4	90.4
367	71.9	74.1	75.1	91.3
396	76.4	75.7	74.6	92.3
425	78.3	77.1	79.6	89.4
489	79.6	86.6	81.8	93.0
535	80.9	78.8	82.3	95.0
549	76.2	78.6	81.9	95.3
577	72.8	77.8	82.1	94.8
607	72.8	77.8	75.6	94.8
642	71.9	77.6	81.1	93.1
667	67.0	76.2	78.9	94.9
695	66.0	74.9	73.4	94.9
730	66.9	76.2	73.7	95.4
758	69.1	77.3	74.5	94.6
786	68.8	76.4	75.7	93.4
848	65.9	71.8	43.5	87.5
879	70.0	76.9	51.2	94.2
913	64.8	74.9	42.1	93.9
941	63.8	73.6	38.8	90.2
977	61.5	73.7	38.4	89.1
997	58.8	73.0	36.2	88.1

(Continued)

TABLE 13 (Concluded)

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1033	55.0	69.9	34.4	86.9
1063	56.2	71.3	36.3	87.8
1091	57.1	71.8	37.0	87.5
1152	61.9	75.1	46.1	90.3
1181	61.2	74.1	47.5	89.6
1218	59.1	73.2	46.2	88.2
1252	62.7	72.1	49.2	91.3
1287	64.9	74.9	46.7	87.5
1312	60.6	73.3	46.5	82.0
1330	58.5	71.2	46.3	83.1
1364	57.7	70.0	49.1	88.1
1420	46.1	63.1	44.4	83.6
1453	50.7	67.4	46.9	85.7
1489	N	58.3	51.4	82.8
1518	N	66.0	46.8	84.7

NOTE: N = no data.

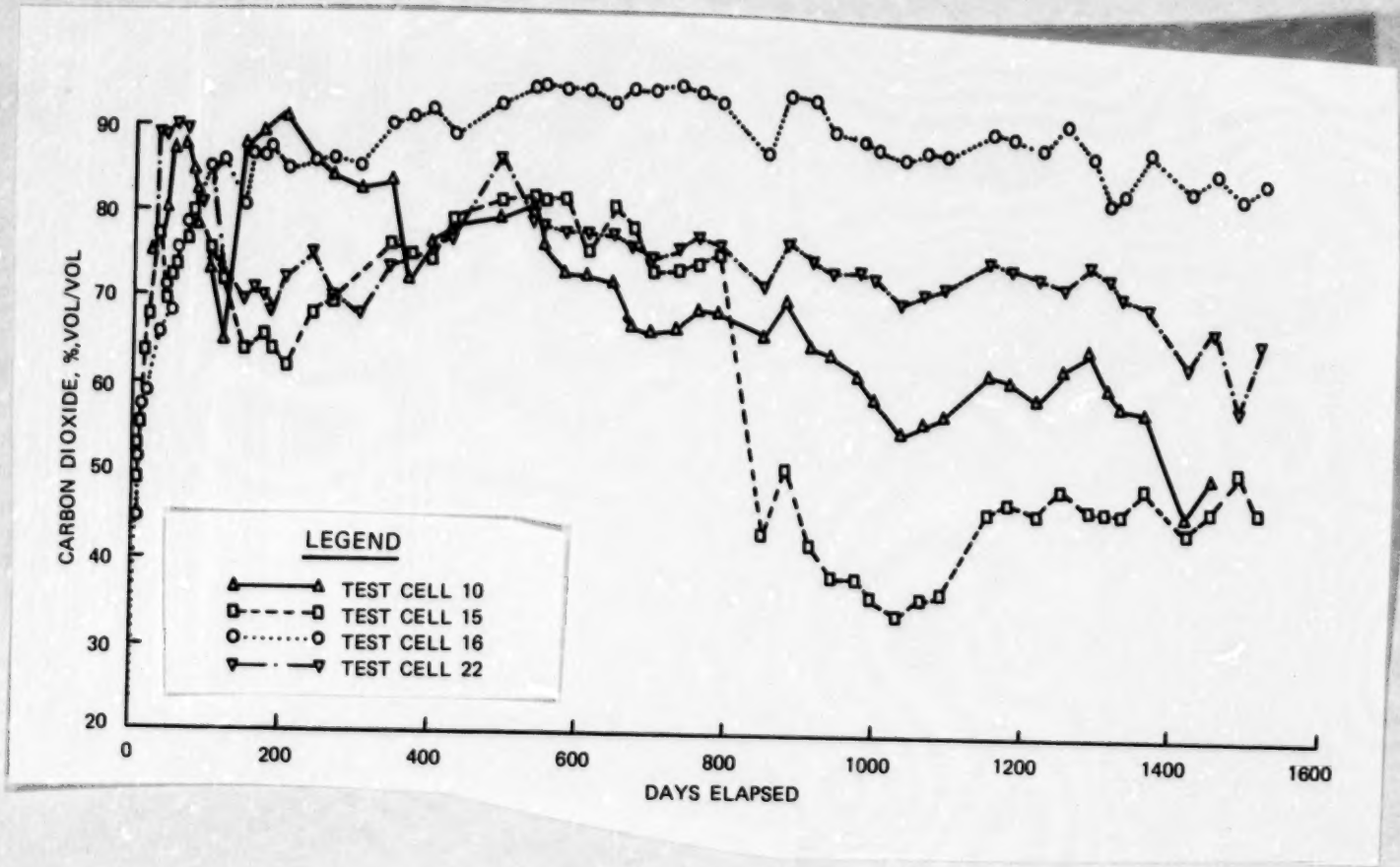

Figure 11. Percent of carbon dioxide in gas from test cells over time of experiment.

TABLE 14. VOLUME OF CARBON DIOXIDE PRODUCED PER KG DRY MSW IN TEST CELLS OVER TWO WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	70.33	23.88	64.42	71.15
21	76.04	63.32	53.58	53.45
35	15.74	73.43	42.00	41.25
49	40.08	62.49	39.43	38.54
63	28.24	34.52	46.01	46.19
77	18.96	7.82	43.03	43.17
91	22.93	1.24	32.22	38.48
105	25.83	45.24	33.53	37.44
119	22.05	68.65	28.32	32.72
133	23.36	4.52	26.72	32.18
147	24.86	7.23	17.98	26.24
161	10.52	6.83	N	17.70
175	15.50	7.62	9.65	16.50
189	3.95	6.57	8.26	11.42
203	20.76	8.74	10.94	13.69
217	17.27	9.06	9.93	12.08
231	10.90	5.84	7.32	8.61
245	9.01	4.66	5.01	5.78
259	7.60	3.58	2.87	3.36
273	7.74	B	3.64	4.23
287	3.92	B	2.48	2.90
301	10.23	5.56	3.47	3.55
315	3.94	0.46	2.45	2.75
329	5.37	4.97	3.42	3.90
343	6.59	7.60	6.61	7.43
357	6.59	4.99	8.24	9.29
371	1.63	0.29	7.10	8.16
385	9.26	7.98	6.46	8.70
399	0.25	0.46	3.67	4.27
413	13.10	16.33	11.97	13.09
427	8.63	9.10	6.60	7.13
441	6.92	6.22	9.64	9.43
455	1.93	3.35	2.61	2.47
469	6.29	3.01	3.64	3.96
483	10.51	9.98	9.79	10.69
497	2.58	1.81	3.07	3.34
511	4.64	0.25	3.90	4.71
525	3.93	3.39	3.58	3.74
539	0.35	0.54	0.71	0.05
553	0.46	0.40	0.06	0.06
567	2.05	B	0.04	0.05
581	4.11	0.35	1.06	1.11
595	3.15	0.52	3.64	4.04
609	2.55	1.56	0.88	1.05
623	4.35	N	2.58	3.00

NOTE: All values in ml/kg dry MSW day. N = no data; B = none detected.

production (Table 15) and before water saturation of the MSW (first leachate was collected between day 250 and 300 in all test cells). An initial high concentration of hydrogen was typically seen (Figure 12) after which small amounts of hydrogen appeared at irregular intervals until approximately day 1000 in all test cells (Table 16).

Much smaller total amounts of hydrogen per kg dry MSW were produced in the smaller test cell than in the larger ones--approximately 15 ml/kg MSW in both small cells and approximately 100 ml/kg MSW in the larger. These are very low rates (compared to Table 17) of gas production. Although methane also showed great variability, hydrogen was the only gas which apparently showed a consistent effect of scale between the two different-sized, test cells. The greater rates of hydrogen production from the drier large test cells follows the pattern found by Chian et al (1977) who found an indirect relationship between rate of hydrogen production and MSW moisture content in their studies.

Methane

Methane production began to be seen in three of the four test cells in a two-week period surrounding day 217, 60 to 90 days after the initial hydrogen production (Table 18). Methane appeared only 30 days before the first leachate was collected from the test cells indicating the waste was approaching water saturation. Methane production continued at low and variable rates for the first 630 days so that a total of 40 to 65 ml/kg MSW had been produced in these three cells during that time. Methane was not detected in the fourth

TABLE 15. VOLUME OF HYDROGEN PRODUCED PER DAY IN TEST CELLS OVER TWO-WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	B	B	B	B
21	B	B	B	B
35	B	B	B	B
49	B	B	B	B
63	B	B	B	B
77	B	B	B	B
91	B	B	B	B
105	B	B	1.0369	B
119	B	B	4.1349	B
133	0.0303	B	3.5040	2.7397
147	0.0848	0.0132	2.1931	2.8663
161	0.1058	0.0276	N	B
175	0.0685	0.0112	B	B
189	B	0.0132	0.3646	1.0388
203	B	0.0189	0.5549	1.5885
217	B	0.0129	0.2579	1.3378
231	B	B	B	0.9031
245	B	B	B	0.6058
259	B	0.0652	0.0605	0.4093
273	B	B	0.0767	0.5145
287	0.0001	B	0.0523	0.3526
301	0.0026	0.0055	0.3010	0.5076
315	0.0010	0.0004	0.2130	0.3934
329	0.0016	0.0088	0.0281	0.1811
343	0.0020	0.0135	0.0544	0.3447
357	0.0036	0.0149	0.2527	0.4016
371	0.0012	0.0010	0.3173	0.3372
385	0.0113	0.0206	0.1634	0.2913
399	0.0006	0.0004	B	0.0873
413	0.0202	0.0114	0.0764	0.2745
427	0.0029	0.0061	0.0521	0.1505
441	0.0023	0.0042	0.0761	0.1989
455	0.0006	0.0023	0.0206	0.0520
469	0.0020	0.0027	0.0280	0.0625
483	0.0034	0.0090	0.0753	0.1687
497	0.0008	0.0016	0.0236	0.0528
511	0.0015	0.0002	0.0229	0.0397
525	0.0012	0.0022	0.0182	0.0165
539	0.0001	0.0003	0.0031	0.0002
553	B	0.0001	0.0001	0.0004
567	B	B	0.0001	0.0002
581	B	0.0002	0.0027	0.0049
595	B	0.0003	0.0135	0.0178
609	B	0.0010	0.0049	0.0046
623	0.0015	N	0.0118	0.0113

NOTE: All values in l/day. N = no data; B = none detected.

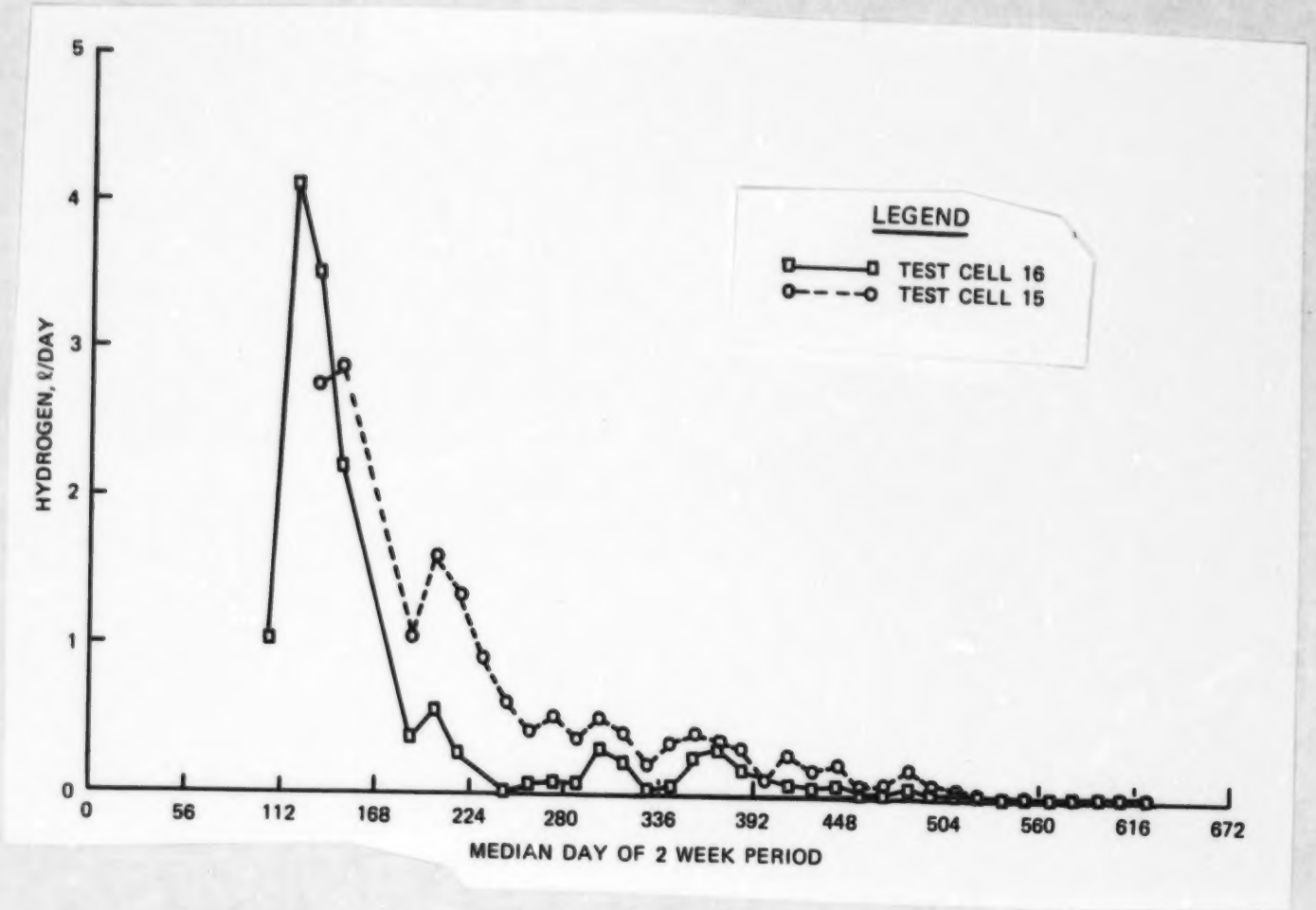

Figure 12. Total volume of hydrogen produced from large test cells summed over 14-day periods.

TABLE 16. PERCENT OF HYDROGEN IN GAS FROM TEST CELLS

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1	B	N	B	B
2	B	N	B	B
6	B	N	B	B
13	B	B	B	B
18	B	B	B	B
30	B	B	B	B
40	B	B	B	B
47	B	B	B	B
53	B	B	B	B
67	B	B	B	B
76	B	B	B	B
83	B	B	B	B
99	B	B	B	B
116	B	B	5.0	B
145	0.6	B	3.7	5.1
157	3.3	1.1	N	B
171	B	B	B	B
181	B	B	B	B
201	B	0.6	1.5	4.7
236	B	B	B	4.3
263	B	4.9	0.7	5.0
299	0.1	0.3	3.0	5.8
341	0.1	0.5	0.3	2.0
367	0.2	1.0	1.6	1.8
396	0.7	0.3	N	0.9
425	0.1	0.2	0.3	0.9
489	0.1	0.3	0.3	0.7
535	0.1	0.2	0.2	0.2
549	B	0.1	0.1	0.3
577	B	0.2	0.1	0.2
607	B	0.2	0.1	0.2
642	0.4	0.2	0.1	0.1
667	B	0.1	0.1	0.2
695	B	B	B	0.1
730	0.7	0.2	0.3	0.6
758	N	N	N	N
786	B	0.1	0.2	B
848	B	0.1	0.2	0.4
879	B	0.1	0.2	0.4
913	B	B	B	0.2
941	B	B	B	0.4
977	B	B	B	0.2
997	B	B	B	B

(Continued)

TABLE 16 (Concluded)

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1033	B	B	B	1.0
1063	B	B	B	0.1
1091	B	B	B	0.2
1152	B	B	B	1.0
1181	B	B	B	B
1218	B	B	0.2	0.2
1252	B	B	B	B
1287	B	B	B	B
1312	B	B	B	B
1330	B	B	B	B
1364	B	B	B	B
1420	B	B	B	B
1453	B	B	B	B
1489	N	B	B	B
1518	N	B	B	B

NOTE: N = no data; B = below detection.

TABLE 17. VOLUME OF HYDROGEN PRODUCED PER KILOGRAM DRY MSW IN TEST CELLS OVER TWO-WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	B	B	B	B
21	B	B	B	B
35	B	B	B	B
49	B	B	B	B
63	B	B	B	B
77	B	B	B	B
91	B	B	B	B
105	B	B	0.4947	B
119	B	B	1.9728	B
133	0.1148	B	1.6718	1.3072
147	0.3213	0.0507	1.0464	1.3676
161	0.4011	0.1061	N	B
175	0.2598	0.0431	B	B
189	B	0.0509	0.1740	0.4956
203	B	0.0728	0.2648	0.7579
217	B	0.0495	0.1231	0.6383
231	B	B	B	0.4309
245	B	B	B	0.2891
259	B	0.2500	0.0289	0.1953
273	B	B	0.0366	0.2455
287	B	B	0.0250	0.1683
301	0.0099	0.0213	0.1436	0.2422
315	0.0039	0.0018	0.1016	0.1877
329	0.0064	0.0339	0.0134	0.0864
343	0.0079	0.0518	0.0260	0.1645
357	0.0139	0.0574	0.1206	0.1916
371	0.0046	0.0040	0.1514	0.1609
385	0.0431	0.0792	0.0780	0.1390
399	0.0023	0.0019	B	0.0417
413	0.0383	0.0438	0.0365	0.1310
427	0.0110	0.0236	0.0249	0.0718
441	0.0088	0.0162	0.0364	0.0949
455	0.0025	0.0091	0.0099	0.0248
469	0.0079	0.0104	0.0134	0.0298
483	0.0132	0.0346	0.0359	0.0805
497	0.0032	0.0063	0.0113	0.0252
511	0.0058	0.0009	0.0109	0.0190
525	0.0049	0.0086	0.0087	0.0079
539	0.0004	0.0014	0.0015	0.0001
553	B	0.0005	0.0001	0.0002
567	B	B	0.0001	0.0001
581	B	0.0009	0.0013	0.0024
595	B	0.0014	0.0064	0.0085
609	B	0.0040	0.0023	0.0022
623	0.0058	N	0.0057	0.0054

NOTE: All values in ml/kg dry MSW day. N = no data; B = none detected.

TABLE 18. VOLUME OF METHANE PRODUCED PER DAY IN TEST CELLS OVER TWO-WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	B	B	B	B
21	B	B	B	B
35	B	B	B	B
49	B	B	B	B
63	B	B	B	B
77	B	B	B	B
91	B	B	B	B
105	B	B	B	B
119	B	B	B	B
133	B	B	B	B
147	B	B	B	B
161	B	N	B	B
175	B	B	B	B
189	B	B	B	B
203	B	B	B	B
217	0.0049	0.0023	0.0565	B
231	0.0073	0.0044	0.0855	B
245	0.0060	0.0035	0.0585	B
259	0.0252	0.0066	0.0614	B
273	0.0257	B	0.0778	B
287	0.0130	B	0.0530	B
301	0.0261	0.0226	0.1003	B
315	0.0104	0.0018	0.0710	B
329	0.0237	0.0389	0.1125	B
343	0.0291	0.0594	0.2176	B
357	0.0318	0.0474	0.3026	B
371	0.0084	0.0030	0.2777	B
385	0.0515	0.0870	0.2692	B
399	0.0016	0.0056	0.1652	B
413	0.0983	0.2300	0.6131	0.4140
427	0.0669	0.1294	0.3476	0.2843
441	0.0537	0.0885	0.5079	0.3758
455	0.0166	0.0494	0.1387	0.0965
469	0.0647	0.0554	0.2523	B
483	0.1081	0.1835	0.6777	B
497	0.0265	0.0334	0.2127	B
511	0.0547	0.0047	0.3102	B
525	0.0500	0.0742	0.3015	B
539	0.0045	0.0119	0.0608	B
553	0.0066	0.0095	0.0054	B
567	0.0302	B	0.0044	B
581	0.0612	0.0095	0.0978	B
595	0.0481	0.0141	0.3458	B
609	0.0398	0.0420	0.0885	B
623	0.0696	N	0.2607	0.0020

NOTE: All values in l/day. N = no data; B = none detected.

cell (large cell #16) until approximately day 410 and then it was produced only briefly (6 to 8 weeks). As can be seen in Figure 13 and Table 19, the percent of methane in the gases from all of the test cells continued to gradually rise over the 1500 days of the experiment. The small test cells consistently produced the gases richest in methane having at around 12% for cell #10 and over 25% for cell #22 at the end of the experiment.

Both of the larger test cells were also showing rapidly increasing methane content in gas samples collected toward the end of the experiment. Test cell 15 began producing methane at about the same time and at the same rate as test cell 10, but the percentage of methane gas declined at the same time that a high nitrogen concentration was detected and the carbon dioxide content decreased. Apparently, either a leak of outside air developed during this time, or a bloom of denitrifying bacteria appeared in the cell. A leak is the more plausible explanation. After approximately day 1100, the nitrogen levels began to decrease and the carbon dioxide levels increase to more typical levels. At this same time, the percentage of methane in the gas coming from cell 15 began to increase at a rapid rate; evidently the methanogenic bacteria resumed their development at this time.

Test cell 16 did not produce over 3% methane over the entire length of the study, attaining over 1% methane only after about 1300 days. It also maintained the highest carbon dioxide levels, consistently around 90%, and the lowest nitrogen percentages, typically less than 10%, although it produced the most total gases. Leachates from this test cell appeared similar to those from the other test cells for pH (5 to 5.7) and alkalinity

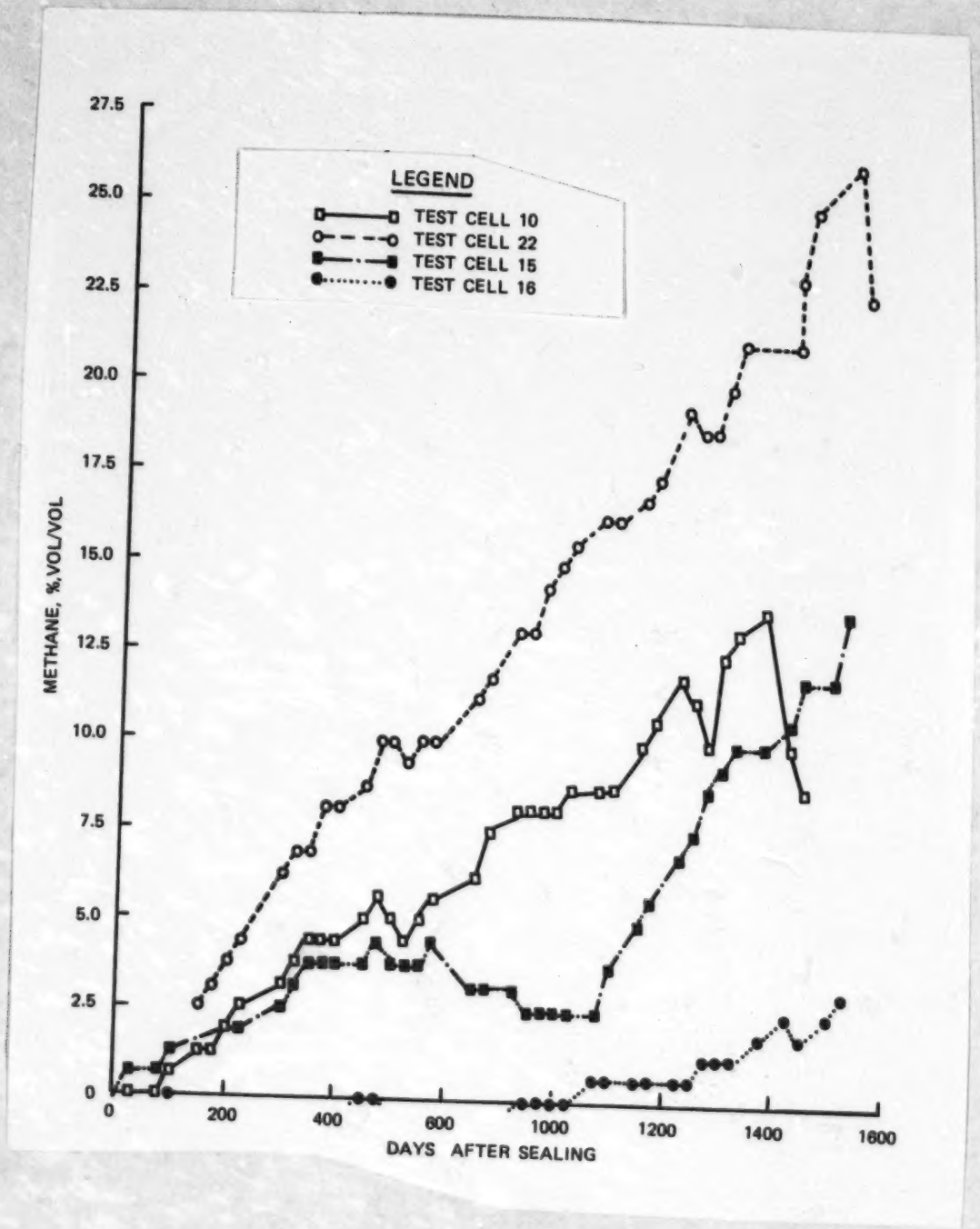

Figure 13. Percent of methane in gases from test cells over duration of the experiment.

TABLE 19. PERCENT OF METHANE IN GAS FROM TEST CELLS

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1	B	N	B	B
2	B	N	B	B
6	B	N	B	B
13	B	B	B	B
18	B	B	B	B
30	B	B	B	B
40	B	B	B	B
47	B	B	B	B
53	B	B	B	B
67	B	B	B	B
76	B	B	B	B
83	B	B	B	B
99	B	B	B	B
116	B	B	B	B
145	B	B	B	B
157	B	B	B	B
171	B	B	N	B
181	B	B	B	B
201	B	B	B	B
236	0.2	0.2	0.4	B
263	0.2	0.5	0.7	B
299	0.8	1.0	1.0	0.1
341	1.4	2.2	1.2	B
367	1.4	2.9	1.4	B
396	1.9	3.5	1.6	B
425	2.3	4.2	2.0	1.7
489	3.1	6.1	2.7	B
535	3.9	6.6	3.3	B
549	4.1	7.1	3.5	B
577	4.1	8.1	3.6	B
607	4.3	8.0	3.6	B
642	4.7	8.9	4.0	0.1
667	5.5	9.8	4.4	0.3
695	4.9	9.9	3.8	B
730	4.6	9.2	3.7	B
758	4.9	10.2	4.0	B
786	5.4	10.1	4.4	B
848	6.5	11.0	2.9	B
879	7.4	11.8	3.4	B
913	8.1	12.9	3.0	B
941	8.3	13.3	2.6	0.1
977	8.4	14.3	2.8	0.2
997	8.3	14.8	2.7	0.2

(Continued)

TABLE 19 (Concluded)

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1033	8.7	15.8	2.7	0.3
1063	8.7	16.0	2.2	0.4
1091	9.0	16.4	3.7	0.5
1152	9.9	16.8	4.9	0.6
1181	10.9	17.7	5.6	0.7
1218	12.0	19.2	7.0	0.9
1252	11.5	18.6	7.3	0.9
1287	10.2	18.7	8.5	1.5
1312	12.4	19.9	9.4	1.3
1330	12.9	21.5	9.8	1.5
1364	13.5	22.9	9.8	1.8
1420	9.8	21.4	10.9	2.2
1453	8.8	25.1	11.8	2.1
1489	N	22.7	11.7	2.5
1518	N	26.2	13.5	2.9

NOTE: N = no data; B = none detected.

(∿2500 mg/1), but had chemical oxygen demand three times larger than other leachates (averaging 30,000 mg/1), and biochemical oxygen demand (∿ 11,000 mg/1) and specific conductivities (∿ 8000 μmho/cm) approximately double those of other leachates. It appears that the conditions in test cell 16 were not conducive to growth of hydrogen-producing or methanogenic bacteria until very late in the experiment (after about day 1200). No reason for this delayed development of methanogenesis could be determined.

Nitrogen

The percentage of nitrogen in the effluent gases dropped rapidly after the test cells were sealed reaching levels of only 3 to 10% within 40 to 60 days (Figure 14) (Table 20). Evidently, this phase represents the purging of the residual nitrogen out of the voids and headspace in the test cell by rapid carbon dioxide evolution. However, after this initial drop in nitrogen concentration, the relative levels of nitrogen increased to a second maximum from about day 100 to 200 in 3 of the 4 test cells (not in cell #16). The second peak of nitrogen in the test cell effluent is believed to be the product of a normal population of denitrifying bacteria whose population appears to peak around day 200 and then slowly decline as the production of methane begins to become appreciable. This pattern is especially true for test cell 22 which appears to have the most "typical" pattern of methane production beginning at this time. Test cell 10, which had a consistently high nitrogen percentage after day about 300 (20 to 30%), showed methane production rates about one-half those of the other small cell (#22).

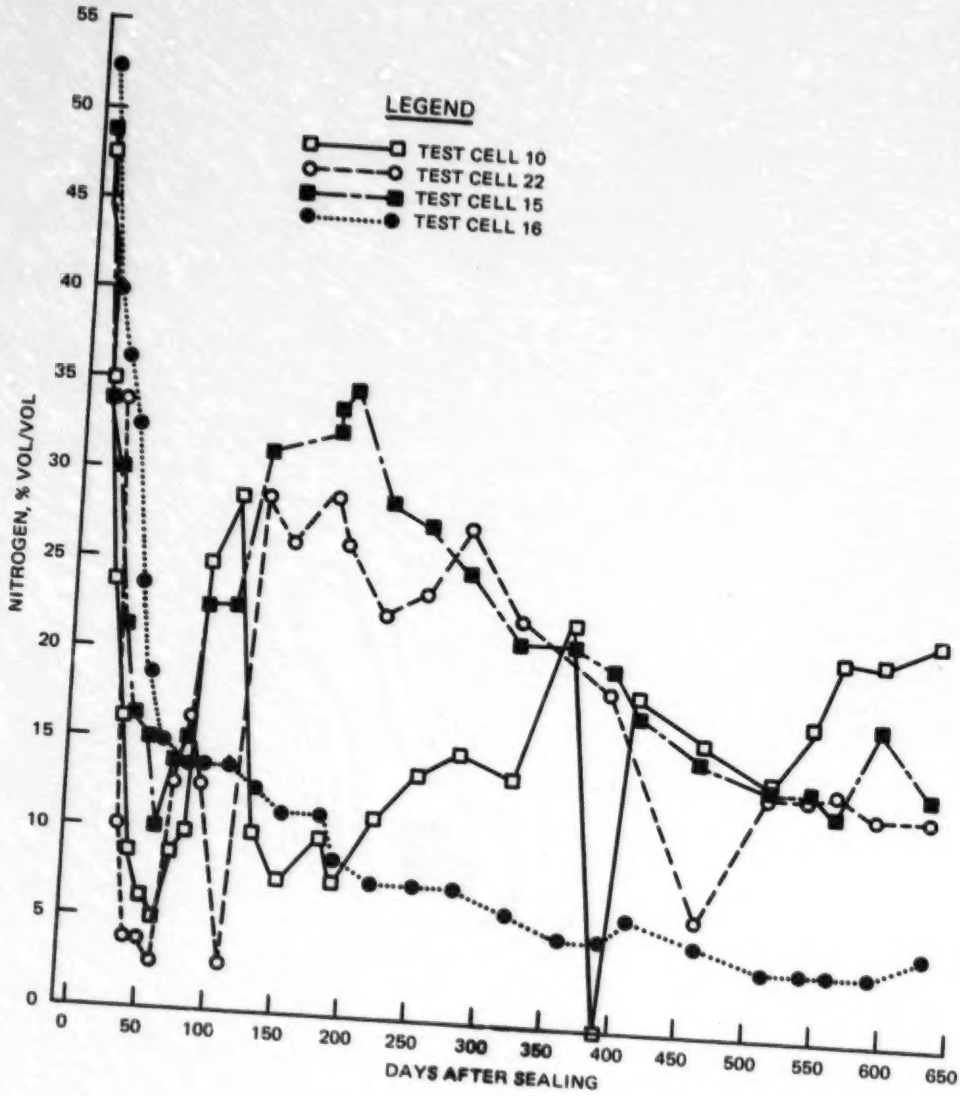

Figure 14. Percent of methane in gases from test cells over duration of the experiment.

TABLE 20. PERCENT OF NITROGEN IN GAS FROM TEST CELLS

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1	52.1	N	48.3	52.7
2	47.1	N	44.6	46.2
6	44.0	N	42.4	40.3
13	34.7	33.8	34.0	38.7
18	24.3	34.1	30.3	36.6
30	16.6	10.1	21.4	32.3
40	8.2	5.8	11.9	24.0
47	7.6	4.1	16.4	18.6
53	6.2	3.6	14.9	18.9
67	5.6	2.9	9.9	15.4
76	8.2	12.6	13.9	12.5
83	10.4	16.4	14.8	13.8
99	25.1	13.1	22.1	14.2
116	28.5	2.3	22.4	13.5
145	10.1	28.8	30.7	13.1
157	7.8	25.9	N	11.4
171	9.6	28.5	33.1	11.6
181	9.6	30.1	34.3	10.9
201	7.6	25.8	35.2	9.1
236	10.9	22.7	29.3	7.4
263	13.2	23.2	27.6	7.4
299	15.2	27.7	25.5	6.9
341	13.8	22.7	20.8	6.1
367	22.6	20.7	20.7	5.6
396	0.1	18.9	20.3	5.4
425	18.5	17.5	17.2	6.6
489	16.0	5.8	14.4	4.9
535	14.1	13.2	13.3	3.9
549	17.9	13.4	13.6	3.8
577	21.4	13.5	13.0	4.1
607	21.2	13.0	18.0	3.9
642	22.6	12.7	13.9	5.4
667	26.2	13.0	15.7	4.0
695	27.0	13.2	20.8	4.1
730	26.9	13.1	21.1	3.7
758	23.9	11.2	19.1	3.8
786	22.5	10.6	17.5	3.7
848	19.7	8.9	29.3	3.0
879	18.8	8.9	41.5	3.3
913	24.3	9.7	51.8	3.8
941	26.2	11.5	56.1	8.2
977	27.4	10.1	55.2	8.8
997	30.8	10.1	58.5	9.7

(Continued)

TABLE 20 (Concluded)

Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
1033	33.9	12.4	60.7	11.3
1063	33.4	11.1	59.1	10.5
1091	31.8	9.5	56.2	10.2
1152	27.9	8.1	48.6	9.1
1181	27.6	7.8	45.9	9.2
1218	28.6	7.6	46.2	10.5
1252	25.4	8.8	42.8	8.0
1287	24.3	6.4	43.9	10.7
1312	26.3	6.7	43.3	15.0
1330	27.9	7.1	43.1	14.0
1364	28.3	7.0	40.4	9.9
1420	42.5	13.9	43.1	13.7
1453	39.3	7.3	40.6	12.0
1489	N	17.1	36.4	14.1
1518	N	7.6	39.2	12.4

NOTE: N = no data.

Actual volumes of nitrogen evolved per day for the first 630 days are shown in Table 21 and volumes released per kg dry weight of MSW per day are shown in Table 22. The large increase in nitrogen percentages in effluent gas from test cell 15 after day 800 was accompanied by a similar decline in carbon dioxide and methane percentages as has been discussed. Large test cell 16 also did not respond in the same manner as the other three test cells, as it showed only the initial decline in nitrogen, maintaining very consistent percentages of nitrogen of around 3 to 4%. Only after about day 900 did the nitrogen percentages begin to rise to a second, consistent level of about 10 to 12%--approximately at the time when low levels of methane began to appear in its effluent. Production of nitrogen by denitrifying bacteria appears to be as variable as methane production both between cells and over time in the same cell. Walsh and Kinman (1979) show similar levels and variability in nitrogen levels in similar sized MSW test cells. No environmental factor or leachate characteristic could be correlated with nitrogen fluxuations in the gas phase.

TABLE 21. AVERAGE VOLUME OF NITROGEN PRODUCED PER DAY IN TEST CELLS OVER TWO-WEEK PERIODS

Median Day	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	14.69	3.29	103.82	119.98
21	6.77	9.20	48.23	65.23
35	0.89	1.54	19.87	35.32
49	0.83	0.82	17.27	21.93
63	0.49	0.29	14.74	20.70
77	0.49	0.18	15.57	15.16
91	1.52	0.06	16.48	13.79
105	2.50	4.02	20.84	12.93
119	2.57	6.49	18.52	10.80
133	1.27	0.45	23.37	10.84
147	0.72	0.74	18.19	8.63
161	0.25	0.65	N	4.87
175	0.41	0.78	10.21	4.58
189	0.11	0.62	9.76	2.65
203	0.45	0.81	13.02	3.07
217	0.46	0.80	10.41	2.46
231	0.36	0.46	6.59	1.55
245	0.30	0.36	4.51	1.04
259	0.31	0.30	2.38	0.59
273	0.32	B	3.02	0.75
287	0.16	B	2.06	0.51
301	0.49	0.59	2.55	0.60
315	0.19	0.04	1.81	0.46
329	0.23	0.40	1.95	0.55
343	0.28	0.61	3.77	1.05
357	0.43	0.37	4.74	1.24
371	0.13	0.02	4.10	1.04
385	0.54	0.55	3.71	1.10
399	0.01	0.03	2.09	0.52
413	0.64	0.97	5.69	1.94
427	0.53	0.53	2.99	1.10
441	0.43	0.36	4.36	1.45
455	0.11	0.18	1.18	0.38
469	0.33	0.05	1.34	0.43
483	0.55	0.17	3.61	1.18
497	0.13	0.03	1.13	0.37
511	0.22	0.00	1.35	0.44
525	0.18	0.14	1.21	0.32
539	0.01	0.02	0.24	0.00
553	0.02	0.02	0.02	0.00
567	0.15	B	0.01	0.00
581	0.31	0.01	0.35	0.10
595	0.24	0.02	1.44	0.35
609	0.19	0.06	0.44	0.09
623	0.34	N	1.17	0.29

NOTE: All values in 1/day. N = no data; B = none detected.

TABLE 22. VOLUME OF NITROGEN PRODUCED PER KG DRY MSW FOR TEST CELLS OVER TWO-WEEK PERIODS

Median Day of Two Week Period	Small Test Cells		Large Test Cells	
	#10	#22	#15	#16
7	55.66	12.61	49.53	57.24
21	25.67	35.26	23.01	31.12
35	3.40	5.93	9.48	16.85
49	3.14	3.16	8.24	10.46
63	1.88	1.14	7.03	9.87
77	1.87	0.69	7.43	7.23
91	5.77	0.25	7.86	6.58
105	9.47	15.41	9.94	6.17
119	9.74	24.90	8.83	5.15
133	4.83	1.74	11.15	5.17
147	2.74	2.83	8.68	4.12
161	0.94	2.49	N	2.32
175	1.55	3.02	4.87	2.19
189	0.42	2.39	4.65	1.26
203	1.73	3.13	6.21	1.46
217	1.75	3.07	4.97	1.17
231	1.37	1.76	3.14	0.74
245	1.13	1.41	2.15	0.49
259	1.19	1.18	1.13	0.28
273	1.21	B	1.44	0.35
287	0.61	B	0.98	0.24
301	1.88	2.26	1.22	0.28
315	0.72	0.19	0.86	0.22
329	0.88	1.53	0.93	0.26
343	1.08	2.35	1.80	0.50
357	1.65	1.44	2.26	0.59
371	0.51	0.08	1.95	0.50
385	2.06	2.14	1.77	0.52
399	B	0.11	1.00	0.25
413	2.45	3.73	2.71	0.92
427	2.04	2.06	1.42	0.52
441	1.63	1.41	2.08	0.69
455	0.43	0.69	0.56	0.18
469	1.26	0.20	0.64	0.20
483	2.11	0.66	1.72	0.56
497	0.51	0.12	0.54	0.17
511	0.85	0.01	0.64	0.21
525	0.68	0.56	0.58	0.15
539	0.06	0.09	0.11	B
553	0.10	0.06	0.01	B
567	0.57	B	0.01	B
581	1.21	0.06	0.16	0.04
595	0.92	0.08	0.68	0.17
609	0.74	0.26	0.21	0.04
623	1.29	N	0.56	0.13

NOTE: All values in ml/kg dry MSW day. N = no data; B = none detected.

CHAPTER 5

DISCUSSION

SCALING EFFECTS OF TEST CELL SIZE

Two sizes of test cells were incorporated into the experimental design to provide information on the effects of test cell size on the overall gas production. Through this scaling study, an improved estimate of the value of the results and their application to full-scale, existing landfills may be possible. The larger test cells had over eight times the total volume and incorporated eight times the mass of compacted MSW, but had only four times the top surface area (Table 3). Since the amount of leaching liquid added to the test cells was determined by the surface area exposed, the larger test cells received only one-half of the amount of infiltration per kg of MSW so that the smaller tanks should have come to water saturation much sooner than the larger ones--estimated saturation at day 244 for the small and day 294 for the large test cells. Also note that over both the short- and the long-run (90 and 1510 days in this case, see Table 3) an average of 40% more moisture was retained per kg dry MSW for the small test cells than for the large. No specific reason is known for this larger moisture capacity in smaller test cells unless it is a result of the larger MSW mass or depth, or of the lower leachate addition rates/kg MSW in the large cells.

The smaller test cells should also equilibrate in temperature more rapidly with their surroundings. The larger tanks maintained slightly higher

temperatures over the length of the study due to their higher thermal mass and lower rates of heat dissipation. This may account for their slightly higher daily rate of gas production on a liter per kg MSW basis over the first 630 days of the study. Table 23 compares the average amount of each gas produced by the test cells per kg MSW per day. The larger cells produced approximately 13% more total gas per kg MSW per day day than the smaller cells; the larger cells also produced more of the major gases--carbon dioxide and nitrogen. The production of hydrogen and methane appears to be quite variable between the two test cell sizes and large differences between similar test cells were found, especially between the two large test cells. A large variation in gas production between their 55 gallon (208 1) drum gas test cells was also seen by Chian et. al. (1977). The relative rates and kinds of bacterial activity in the MSW must be easily influenced by MSW composition and conditions.

Higher gas production from the large test cells is also seen when data for the first 100 days is compared. The larger cells averaged 68.1 ml/kg/day total gas production over first 100 days, which was 23% larger than the 55.4 ml/kg/day from the small cells for the same period. The higher average temperatures in the larger cells could account for the more rapid decomposition and greater major gas production in these cells.

The two different sizes of test cells produced comparable amounts of nitrogen and methane but the larger test cells produced six times more hydro gen than the small test cells (Table 23) over the first 630 days. The size of the test cells has a significant effect on the rate of gas production and

TABLE 23. COMPARISON OF GAS PRODUCTION BY THE SMALL AND LARGE TEST CELLS

Gas	Total Volume* of Gas Produced per kg Dry MSW					
	Small Test Cells			Large Test Cells		
	#10	#22	Avg	#15	#16	Avg
Total gas	18.01	17.50	17.75	20.03	20.15	20.09
Oxygen (Argon)**	0.18	0.13	0.15	0.12	0.10	0.11
Carbon Dioxide	13.2	11.9	12.5	13.2	14.9	14.0
Hydrogen	0.028	0.023	0.025	0.148	0.169	0.158
Methane	0.089	0.104	0.096	0.064	0.012	0.038
Nitrogen	3.59	3.17	3.38	4.56	3.95	4.25

NOTE: Components do not sum to the stated total because water vapor is not included in the table; all values are accumulated total volumes to day 630.

* All values in ml/kg MSW day.

** Oxygen and argon not distinguished in analyses.

the composition of the gas produced. This effect may be due to temperature effects and the speed with which smaller test cells in this study reached saturation. It appears that reasonable estimates of the behavior of the decomposition of waste and the evolution of the various gases can be made from landfill simulators such as those used in this study if effects of scaling are considered.

DEVELOPMENT OF GAS PRODUCTION

The typical sequence of events which occur in the development of gas production in buried refuse or other anaerobic digesters has been broken into four stages that are related to the microfloral development responsible for gas production (Farquhar and Rovers, 1973; McCarty, 1964; Toerien, 1969). The first, or "aerobic," stage seen in the landfill is the oxygen-depleting, aerobic decomposition of the more easily metabolized materials (Ham and Bookter, 1982). This stage involves the uptake of the residual oxygen in the air-filled voids in the MSW as placed in the landfill. In this study, the majority of the oxygen was exhausted before the first gas sample had been taken for analysis on the first day after the tanks had been sealed. Thus, the initial part of the oxygen depletion phase was not seen possibly due to the rapid, aerobic decomposition at the warm temperatures of the MSW when it was placed (Rovers and Farquhar, 1973). The oxygen which is taken up during this time is replaced in approximately equimolar amounts by carbon dioxide produced by aerobic respiration. The reduced gases such as hydrogen or methane are not produced in this phase due to the high oxidation-reduction potential in the presence of oxygen (Engineering-Science, 1965). Very little displacement of nitrogen is seen during this phase.

After the depletion of the oxygen in the refuse, the gas production pattern enters the second phase, which is the non-methanogenic, anaerobic phase. During this time, the concentration of carbon dioxide in the outflowing gas peaks, nitrogen is displaced by large volumes of carbon dioxide being produced, and hydrogen begins to be seen (Farquhar and Rovers, 1973). In the three test cells which went on to produce appreciable methane in this study (test cells 10, 16 and 22), nitrogen in the out flowing gas decreased in concentration at a much slower rate than oxygen, taking 40 to 60 days to reach its minimum concentration of approximately 5 to 10%. During the later portion of this phase (days 75 to 150), nitrogen levels increased to a second relatively constant level of between 15 and 30% of the gas volume. This increase in nitrogen may have been due to denitrifying bacteria in the refuse mass which use nitrate as a terminal oxidant under anaerobic conditions (Farquhar and Rovers, 1973). During the latter part of this nitrogen increase (between day 100 and 150), hydrogen began to be produced. Carbon dioxide also reached its maximum concentrations and then maintained fairly constant proportions throughout the rest of the experiment, falling only as it was displaced by the beginning of methane production. Near the end of this phase (i.e., before methane production), leachate began to be produced from the test cells (day 250 to 300) indicating that the refuse arrived at water saturation.

In phase three the high levels of carbon dioxide and the presence of short-chain, volatile, organic acids from refuse decomposition bring about conditions in the test cells which are conducive to the development of the methanogenic bacteria which are present in soil and refuse (Toerien, 1969). These bacteria obtain energy from two reactions, from the reduction of carbon

dioxide through the addition of hydrogen to form methane and water, and from the cleavage of acetate into methane and carbon dioxide (McCarty, 1964). Nitrogen gas is also commonly produced through the denitrification of nitrite and nitrate. The first part of the methane producing phase (phase 3), is termed the unsteady methanogenic stage (Farquhar and Rovers, 1973). Methane levels are increasing and changing unpredictably during the phase due to the sensitive nature of these bacterial populations. During phase three, hydrogen disappears because it is rapidly used in the production of methane (Toerien, 1969) and both carbon dioxide and nitrogen concentrations drop to some stable levels. Completion of the first three phases have been reported to take from about 180 days (Ramaswamy, 1970) to 250 days or more (Rovers and Farquhar, 1973) depending upon environmental factors (such as temperature and moisture content) and the type of refuse and landfilling practices are used.

Phase four occurs when the gas composition and production rates come to stable levels for the prevailing conditions of temperature, moisture and refuse type. Landfill gases during this phase typically have compositions of from 50 to 70% methane and from 30 to 50% carbon dioxide (Colonna, 1976; DeWalle, Chian and Hammerberg, 1978; Engineering-Science, Inc. 1965). This corresponds well to the gas compositions found for biodigestors and for sewage sludge digestors (Farquhar and Rovers, 1973; Toerien, 1969). It is believed that none of the test cells in this experiment reached stage four over the full 1500-day study, although it appears as if cells 10, 15 and 22 were approaching stability when the experiment was terminated. If methane

concentrations in the gas phase do not reach about 50% by volume, then methane production is very likely being retarded by some unknown conditions in the test cells. This is true especially if hydrogen continues to be detected along with methane as it was in this study. The retarding factors may include temperature, pH and nutrient availability.

FACTORS AFFECTING GAS METHANE PRODUCTION

Several factors have been found to influence gas production rates and composition (DeWalle et. al., 1977; Farquhar and Rovers, 1973; Walsh and Kinman, 1979). Moisture content must be relatively high; moisture contents of over 80% of the dry wt are necessary for maximum total gas production. High infiltration rates, however, can retard methane fermentation due to an input of dissolved oxygen in the water and the dilution of the nutrients in pore fluid (Fungaroli, 1971). Moisture did not appear to be a limiting factor in this experiment as the moisture content over the first 900 days in the small test cells averaged about 123% of the dry MSW weight and 82% for the large over the first 180 days (Table 3) and generally increased uniformly from then on (Table 4).

Although methane production takes place over wide temperature ranges, temperatures around 35°C appear to promote the maximum amounts of methane for mesophilic bacterial populations (Toerien, 1969). Temperatures in the MSW test cells in this experiment averaged between 30°C and 35°C over the first 100 days of the experiment after which temperatures slowly dropped to around 22°C in the winter and 26°C in the summer months. Slowing of gas production

may have resulted in the later parts of this study from the lower-than-optimum temperatures. Temperature differences between the small and large test cells may account for the differences in gas production between them.

Optimal pH for overall gas production from sewage sludge was reported to be around 7.0. Alkalinities greater than 2000 mg/l (calcium carbonate equivalent) are necessary for maximum methane production rates; similar conditions have been assumed to hold for MSW in landfills (Farquhar and Rovers, 1973). Leachate pH's and alkalinities in leachates from these test cells were not at optimum. The pH values for all leachates averaged between 5.0 and 5.5, and alkalinities typically were much less than 2000 mg/l. These factors may account for the slow development of methane production in the test cells in this study.

Landfill leachates are very likely to contain materials derived from the MSW refuse. Any industrial and household wastes which are included may be toxic to or inhibit the growth of methanogenic bacteria. Further, the nutritional requirements supplied in the leachate may also not be optimum for methane production. Maximum gas production rates have been found to occur when the growth medium had a carbon-to-nitrogen (C/N) ratio of approximately 16 and levels of ferrous iron of over 20 mg/l (McCarty, 1964). The C/N ratio of the leachates collected in this experiment averaged 13.5 for the small and 10.6 for the large test cells which is below optimum but should not be inhibitory. Also ferrous iron levels averaged well over 450 mg/l for both cell sizes.

The typical patterns of gas production rates and compositions were found from all four MSW test cells included in this study. Although the stable methane production phase (phase four) was not established in any of the test cells over the 1500 days of the experiment, methane levels in outflowing gas was increasing from all test cells at the termination on the experiment. The slow development of the test cells in this study is thought to be because of the low pH and alkalinity values of the landfill leachate, and possibly to the low temperatures in the MSW due to the uninsulated test cell walls, but further experimentation would be necessary to rule out other factors such as toxicants or nutrient limitations.

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